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Ann Arbor

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16. ABSTRACT

In 1974 and 1975, several studies were conducted on southern Lake Huron and outer Saginaw Bay to obtain seasonal data on limnological conditions. In 1974, 44 stations were sampled on each of eight cruises conducted from April to November. Each station was sampled at multiple depths so that more than 200 samples were taken on each cruise. Data obtained for each sample included water temperature, pH, specific conductance, chloride, total phosphorus, soluble reactive silica, nitrate plus nitrite nitrogen, ammonia nitrogen, chlorophyll a, and phaeopigments. In 1975, five special cruises were conducted. Four of these were used to compare phytoplankton productivity and nutrient dynamics in the frontal zone between highly enriched Saginaw Bay and the relatively low productivity waters of southern Lake Huron. One cruise was used to study the effect of the spring thermal bar on the distribution of nutrients and nearshore phytoplankton standing crops. These studies confirm that Saginaw Bay and the nearshore zone of southern Lake Huron have larger concentrations of total phosphorus (the major growth limiting nutrient in the system) and greater standing crops of phytoplankton than the offshore waters. They also show that the nearshore zones, especially on the Canadian shore, differ from the offshore waters to a greater degree during the period of the spring thermal bar than at other times of the year.

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LIMNOLOGICAL CONDITIONS IN SOUTHERN LAKE HURON, 1974 AND 1975

by

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FOREWORD

Limnology of the Great Lakes is a very complex subject and requires the cooperative studies of many investigators to develop an overall understanding. This understanding of how the systems are interrelated is required in the development of pollution management scenarios.

This report brings together many observations and data systhesis resulting from a large field experiment conducted as part of the Upper Lakes Reference Study. The data and interpretations contained in this report have aided greatly in the protection of Lake Huron.

Norbert Jaworski, Ph.D.
Director
Environmental Research Laboratory
Duluth, Minnesota

ABSTRACT

In 1974 and 1975, several studies were conducted on southern Lake Huron and outer Saginaw Bay to obtain seasonal data on limnological conditions. In 1974, 44 stations were sampled on each of eight cruises conducted from April to November. Each station was sampled at multiple depths so that more than 200 samples were taken on each cruise. Data obtained for each sample included water temperature, pH, specific conductance, chloride, total phosphorus, soluble reactive silica, nitrate plus nitrite nitrogen, ammonia nitrogen, chlorophyll _a_, and phaeopigments. In 1975, five special cruises were conducted. Four of these were used to compare phytoplankton productivity and nutrient dynamics in the frontal zone between highly enriched Saginaw Bay and the relatively low productivity waters of southern Lake Huron. One cruise was used to study the effect of the spring thermal bar on the distribution of nutrients and nearshore phytoplankton standing crops. These studies confirm that Saginaw Bay and the nearshore zone of southern Lake Huron have larger concentrations of total phosphorus (the major growth limiting nutrient in the system) and greater standing crops of phytoplankton than the offshore waters. They also show that the nearshore zones, especially on the Canadian shore, differ from the offshore waters to a greater degree during the period of the spring thermal bar than at other times of the year.

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SECTION 1

INTRODUCTION

Studies on southern Lake Huron were conducted in 1974 and 1975 as part of the investigations of Lake Huron and Lake Superior by the Upper Great Lakes Reference Group. These studies, including results we are presenting in this report, have been summarized in previous publications (International Joint Commission, 1976; International Joint Commission, 1977a; International Joint Commission, 1977b). Results obtained as part of our investigation of southern Lake Huron were included in the reports by the Upper Great Lakes Reference Group and are referred to as data from the Great Lakes Research Division (GLRD) which is a division in the Center for Great Lakes and Marine Waters, University of Michigan.

We conducted two different types of research activities: in 1974, eight cruises were scheduled from April to November to sample a variety of physical, chemical, and biological variables, and in 1975, two special projects were undertaken. In the first 1975 study, processes were compared in the interface region between Saginaw Bay, a highly enriched area, and open Lake Huron (Moll et al., In press). The second 1975 study was used to determine the influence of the spring thermal bar on nearshore chemical and biological conditions. Results of the 1974 investigations are presented in Sections 3-5 and those for the 1975 studies in Sections 6 and 7.

A number of reports compiled as part of the studies by the Upper Great Lakes Reference Group have been published. Two of these reports resulted from data collected at the same stations we occupied in 1974; one deals with the rotifers of Saginaw Bay and southern Lake Huron (Stemberger et al., 1979), and the other deals with the phytoplankton in southern Lake Huron (Stoermer and Kreis, In press). During 1974, stations in Saginaw Bay were sampled extensively by Smith et al. (1977) and water circulation was studied by Danek and Saylor (1975). Zooplankton collected during this study of Saginaw Bay have been examined (Stemberger et al., 1979), as have the phytoplankton (Stoermer et al., In prep.). Bierman et al. (In press) have utilized some of these data to develop and calibrate a phytoplankton model for Saginaw Bay that predicts changes in phytoplankton composition at the class level. Several papers dealing with atmospheric inputs of phosphorus to southern Lake Huron have been published (Delumyea and Petel, 1977; Delumyea and Petel, 1978; Delumyea and Petel, 1979). Reports of the chemical limnology of Georgian Bay (Warry, 1978a) and the North Channel (Warry, 1978b) of Lake Huron and on the phytoplankton of Georgian Bay (Nicholls et al., 1975) have been published. These papers provide an extensive amount of data on physical, chemical, and biological conditions in Lake Huron during 1974 and 1975.

In addition to obtaining data on water quality characteristics in southern Lake Huron, our study was designed with two specific purposes. First, we were interested in the effect of transport of water and materials from Saginaw Bay on water quality in southern Lake Huron. As a consequence, three transects of stations across Saginaw Bay were established so spatial relationships could be studied. Second, we wanted to study dynamics of environmental processes prior to and during the period of spring warming and thermal bar formation. To attain this objective the eight cruises were unequally spaced in time with the first four cruises being scheduled between the end of April and mid June.

Several additional studies that include valuable background information on Saginaw Bay and Lake Huron should be cited. These include studies on physical and chemical limnology (Ayers et al., 1956; Johnson, 1958; Beeton et al., 1967; Sloss and Saylor, 1975), chlorophyll and primary production (Glooschenko and Moore, 1973; Watson et al., 1976), historical conditions (Freedman, 1974; Goodell, 1977), and biological, chemical and physical limnology (Schelske and Roth, 1973).

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SECTION 2

CONCLUSIONS

Water quality in the open waters of southern Lake Huron is very good, although inputs from shoreline sources in the United States and Canada affect water quality in adjacent nearshore zones. Most of the nearshore loading from the shoreline in the United States originates from Saginaw Bay, and from the Canadian shoreline, the sources appear to be the Maitland and Bayfield Rivers. Effects of nutrient loading in the Canadian nearshore zone are most pronounced during and after the period of the spring thermal bar.

Transboundary (international) movement of water masses with low water quality is not likely to occur as a result of shoreline inputs from either the United States or Canada. Identifiable water masses have been traced moving north, south, and lakeward from outer Saginaw Bay, but these slugs of water ordinarily will be mixed and diluted greatly with open lake waters prior to crossing the international boundary.

Although transboundary movement is not readily identifiable as discrete parcels of water, there is no question that nutrient inputs from shoreline sources in both the United States and Canada contribute to the subtle long-term changes in water quality that have occurred in southern Lake Huron. Inputs from the southern part of Lake Huron probably have little effect on water quality in northern Lake Huron, primarily because predominant circulation patterns tend to minimize this type of transport and, additionally, allow long periods of time for mixing and dilution of nutrients and other substances and for utilization and loss of nutrients by biological and physical processes.

Comparisons of our data from 1974 with those from the northern part of the lake are not ideal because few data were collected in the northern part during 1974. Our data cannot be used to represent conditions in the entire lake. Phasing differences in seasonal cycles that can be caused by latitudinal and morphometric effects make it difficult to compare lake-wide data other than those collected synoptically. Year-to-year comparison of data from the same location can be confounded by year-to-year variations in meteorological conditions and associated seasonal cycles in the lake.

Our limited sampling of Saginaw Bay (restricted to stations in the outer part of the bay) indicates that Saginaw Bay is highly eutrophic compared to the open waters of southern Lake Huron. Saginaw Bay water was readily identifiable by greater chloride and total phosphorus concentrations and by an order of magnitude greater standing crops of chlorophyll a in comparison to the open lake.

Conditions in outer Saginaw Bay were variable from station to station and from cruise to cruise. This variability is a function of complex current patterns and water movement, which are strongly influenced by short-term meteorological events.

Although data collected in our study and by other workers suggest that transport from Saginaw Bay follows several different general patterns, it is likely that the predominant transport pattern is movement of water along the south shore of outer Saginaw Bay, around the thumb, and then southward along the shoreline. Significant movement of water out of the bay must be accompanied by a compensating intrusion of water into the bay. (At certain times of the year, the net exchange of water is from the lake to the bay.)

Seasonal factors play an important part in environmental processes in the southern part of Lake Huron. During the period of the spring thermal bar, water movement and biological processes are different from those that occur in the thermally stratified lake during the summer. Winter conditions would also be different (but these were not studied) in that during this period of the year, the system is either homothermous or partially ice-covered, which would affect currents and water movement.

Our studies and those by others show that phosphorus is the major nutrient that limits phytoplankton growth and controls the standing crop of algae. The results also show that excessive inputs of phosphorus have stimulated diatom growth to the extent that soluble reactive silica levels were reduced to limiting concentrations in and near outer Saginaw Bay during 1974 and 1975. This result is substantive evidence that phosphorus enrichment is excessive and indicates that such an effect in the future may expand over larger areas of southern Lake Huron unless phosphorus inputs can be controlled.

SECTION 3

DESCRIPTIVE PHYSICAL-CHEMICAL LIMNOLOGY

by Claire L. Schelske, David D. Dow, and Laurie E. Feldt

In this section, data on physical-chemical variables and chlorophyll a are presented for the samples collected in 1974 at a depth of 1 m. These data and data for other depths have been utilized also in the analyses presented in Sections 4 and 5.

METHODS

Data presented in this section were collected in 1974 and analyzed according to the methods listed below. In addition, as discussed in the Introduction, these methods and procedures were utilized for specialized studies conducted during 1975. All cruises in both years were conducted from the R/V ROGER R. SIMONS, a vessel provided by the Environmental Protection Agency.

In 1974, eight cruises were conducted on southern Lake Huron, beginning April 28 and ending November 14. There was a cruise each month, with the exception of June when there were two and September when there was none. Originally, 62 station locations were selected for sampling (Figure 3.1). After the first two cruises, it was obvious that it would not be possible to sample all stations on each cruise because the time on station and time to steam between stations were too great. A revised sampling strategy was then adopted that included 44 stations that could be sampled in five days (Figure 3.2). Most of these stations were sampled on the last six cruises -- a list of stations sampled on each cruise is presented in Table 3.1. Vessel operations and scientific activities were designed for a one-shift operation, and consequently, sampling and research operations were terminated each day and started again the following day.

Water samples were taken with 8-liter Niskin bottles at predetermined depths of 1 and 5 m and at 5-, 10-, or 20-m intervals to the bottom; deeper depths were adjusted so that 10 was the maximum number of Niskin bottles used per station (Table 3.2). Water transparency was measured with a white Secchi disc. Temperature at depth was measured with a bathythermograph, and in addition, surface temperature was measured with a mercury thermometer on shipboard.

All methods used on the southern Lake Huron cruises are described in a manual of field and laboratory procedures (Davis and Simmons, 1979). Water

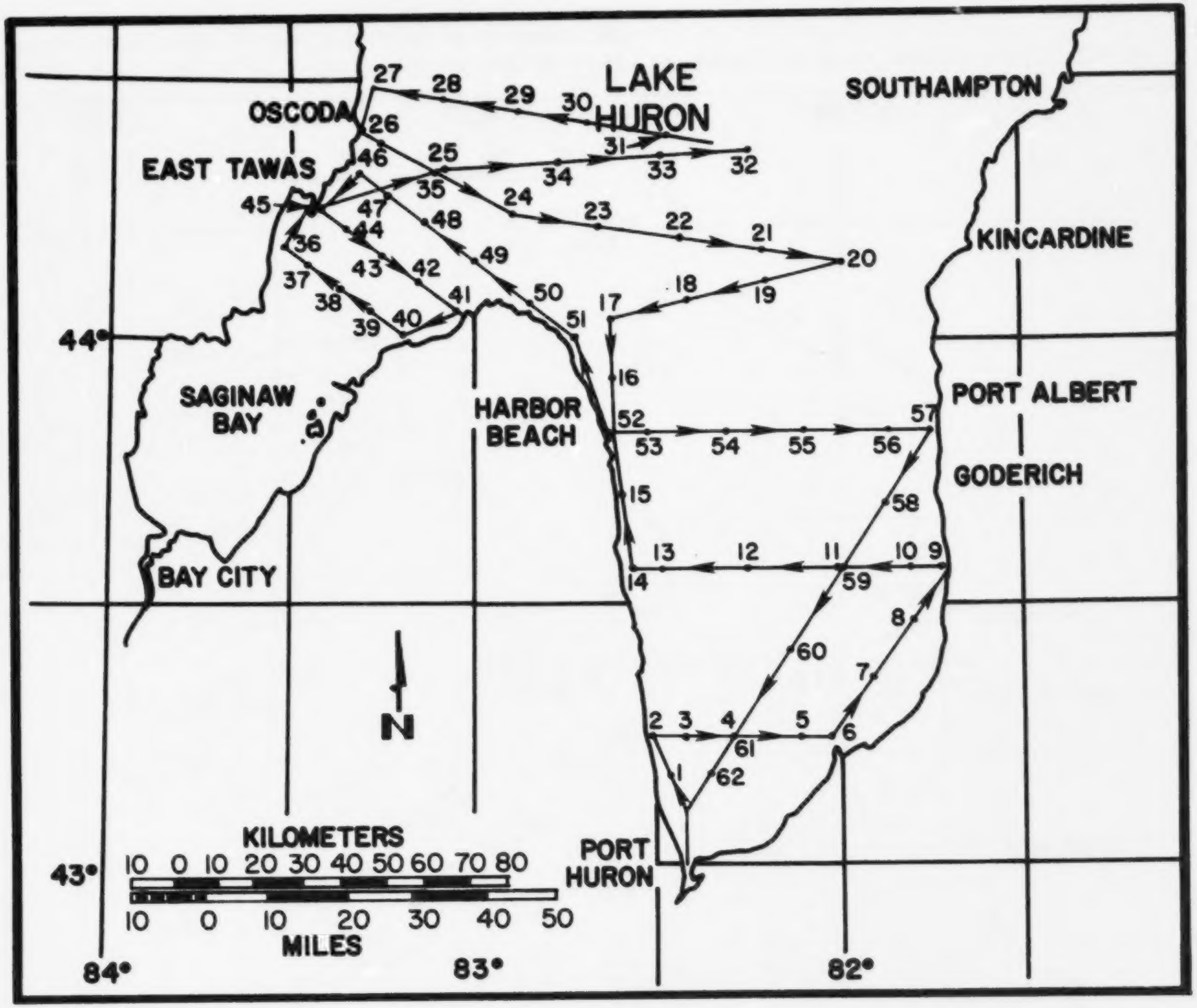
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Figure 3.1. Proposed stations for study of southern Lake Huron, 1974. Cruise plan shown was utilized for Cruises 1 and 2.

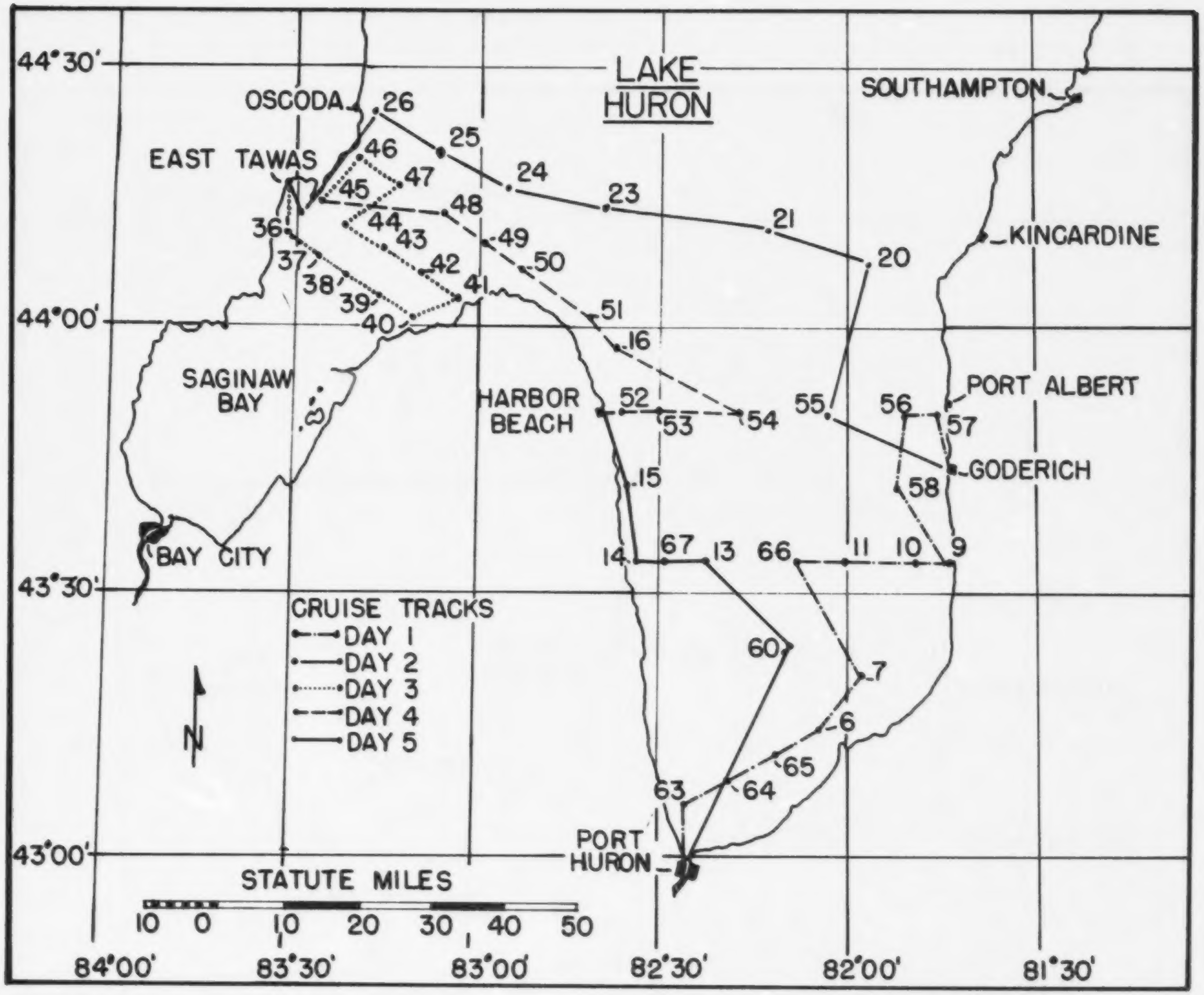

LAKE HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
OSCODA
EAST TAWAS
SAGINAW BAY
HARBOR BEACH
BAY CITY
PORT HURON
CRUISE TRACKS
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
N
STATUTE MILES
10 0 10 20 30 40 50
44°30'
44°00'
43°30'
43°00'
84°00'
83°30'
83°00'
82°30'
82°00'
81°30'
26
25
24
23
21
20
46
47
45
48
44
43
49
50
36
37
38
39
40
41
42
51
16
52
53
54
55
56
57
58
15
14
67
13
66
11
10
9
60
7
6
65
64
63

Figure 3.2. Major stations sampled during study of southern Lake Huron, 1974. Cruise tracks shown were those followed on Cruises 3-8.

TABLE 3.1. STATIONS SAMPLED ON SOUTHERN LAKE HURON DURING 1974

	Cruises (1974)							
Station #	April 28-May 3 1	May 14-17 2	June 4-8 3	June 17-25 4	July 17-29 5	Aug. 26-31 6	Oct. 8-19 7	Nov. 10-14 8
01	x	x						
02	x							
03	x							
04	x							
05	x							
06	x	x	x	x	x	x	x	x
07	x	x	x	x	x	x	x	x
09	0	x	x	x	x	x	0	x
10	0	x	x	x	x	x	x	x
11	x	0	x	x	x	x	x	x
12	x							
13	x	0	x	x	x	x	x	x
14	x	x	x	x	x	x	x	x
15	x	0	x	x	x	x	x	x
16	x	x	x	x	x	x	x	x
17			x					
18		x						
19		x						
20	0	x	x	x	x	x	0	0
21	0	0	x	x	x	x	0	0
22			x					
23	0	x	x	x	x	x	x	x
24	0	x	x	x	x	x	x	x
25	x	0	x	x	x	x	x	x
26	x	0	x	x	x	x	x	x

(continued).

TABLE 3.1. (continued).

	Cruises (1974)							
Station #	April 28-May 3 1	May 14-17 2	June 4-8 3	June 17-25 4	July 17-29 5	Aug. 26-31 6	Oct. 8-19 7	Nov. 10-14 8
27	x							
36	0	x	x	x	x	x	x	x
37	x	x	x	x	x	x	x	x
38	x	x	x	x	x	x	x	x
39	0	x	x	x	x	x	x	x
40	0	x	x	x	x	x	x	x
41	0	x	x	x	x	x	x	x
42	x	x	x	x	x	x	x	x
43	x	x	x	x	x	x	x	x
44	x	0	x	x	x	x	x	x
45	x	x	x	x	x	x	x	x
46	x	0	x	x	x	x	x	x
47	x	0	x	x	x	x	x	x
48	x	x	x	x	x	x	x	x
49	x	x	x	x	x	x	x	x
50	x	x	x	x	x	x	x	x
51	x	x	x	x	x	x	x	x
52	x	x	x	x	x	x	x	x
53	x	x	x	x	x	x	x	x
54	0	0	x	x	x	x	x	x
55	x	x	0	x	x	x	x	x
56	x	x	x	x	x	x	0	x
57	x	x	x	x	x	x	0	x
58	x	x	x	x	x	x	0	x
59	x	x						

(continued).

TABLE 3.1. (continued).

	Cruises (1974)							
Station #	April 28-May 3 1	May 14-17 2	June 4-8 3	June 17-25 4	July 17-29 5	Aug. 26-31 6	Oct. 8-19 7	Nov. 10-14 8
60	x	x	x	x	x	x	x	0
61	x							
62	x							
63	0	x	x	x	x	x	x	x
64	0	x	x	x	x	x	x	x
65	0	x	x	x	x	x	x	x
66	0	x	x	0	x	x	x	x
67	0	x	x	x	x	x	x	x
# stations sampled	38	37	46	43	44	44	38	41

X indicates cruise station was sampled and 0 indicates station that was part of final sampling network but that was not sampled. In addition to final network, 14 stations were sampled once or twice -- see text for additional explanation.

TABLE 3.2. SAMPLING DEPTHS FOR PRIMARY STATIONS OCCUPIED IN SOUTHERN LAKE HURON

Station no.	Sampling depths (m)	
Day 1		
63	1, 5	
64	1, 5, 10, 15	
65	1, 5, 10, 15	
06	1, 5, 10	
07	1, 5, 10, 15, 20, 25	
09	1, 5	
10	1, 5, 10, 15	
11	1, 5, 10, 15, 20, 30, 40, 50, 60	
58	1, 5, 10, 15, 20, 30	Total samples = 40
Day 2		
57	1, 5	
56	1, 5, 10, 15, 20	
20	1, 5, 10, 15, 20, 30, 40	
21	1, 5, 10, 15, 20, 30, 40, 60, 80, 90	
23	1, 5, 10, 15, 20, 30, 40, 50	
24	1, 5, 10, 15, 20, 30, 40, 50, 60	
25	1, 5, 10, 15, 20, 30, 40, 50	
26	1, 5	Total samples = 51
Day 3		
36	1, 5	
37	1, 5, 10, 15	
38	1, 5, 10	
39	1, 5, 10	
40	1, 5	
41	1, 5, 10	
42	1, 5, 10, 15, 20	
43	1, 5, 10, 15, 20, 25	
44	1, 5, 10, 15, 20	
47	1, 5, 10, 15, 20, 30, 40	
46	1, 5	
45	1, 5, 10	Total samples = 45

(continued.)

TABLE 3.2. (continued).

Station no.	Sampling depths (m)	
Day 4		
48	1, 5, 10, 15, 20, 30, 40	
49	1, 5, 10, 15, 20, 30, 40	
50	1, 5, 10, 15	
51	1, 5, 10, 15, 20, 30	
16	1, 5, 10, 15, 20, 30	
55	1, 5, 10, 15, 20, 30, 40, 50, 60, 70, 80	
54	1, 5, 10, 15, 20, 30, 40, 50, 60	
53	1, 5, 10, 15, 20, 30, 40	
52	1, 5, 10, 15, 20	Total samples = 62
Day 5		
15	1, 5	
14	1, 5, 10	
67	1, 5, 10, 15, 20, 25	
13	1, 5, 10, 15, 20, 25	
66	1, 5, 10, 15, 20, 30, 40, 50	
60	1, 5, 10, 15, 20, 30, 40	Total samples = 32

samples were processed as illustrated in the flow chart (Figure 3.3). Samples for soluble chemical analyses were filtered through 47-mm HA Millipore filters that were previously soaked and rinsed several times with distilled-deionized water. These were stored in Nalge conventional polyethylene bottles that were rinsed at least once with excess sample before filling (Schelske et al., 1976).

A Corning pH meter, Model 110 equipped with a digital expanded scale and an automatic temperature compensator, was used on shipboard to measure pH immediately after the samples were taken.

Specific conductance was measured on shipboard with a Leeds and Northrup Model 4866-60 conductivity bridge, corrected to 25°C (Schelske et al., 1974).

Samples for measurements of carbon fixation were obtained at 1 m at all stations and at 1 and 5 m at selected stations. Water samples (265 ml) were collected in glass-stoppered Pyrex bottles, injected with 2.0 $\mu Ci\,^{14}C$, and incubated in a shipboard incubator with 0, 1, or 2 layers of plastic window screen. The screens reduced light intensity, simulating depth in the water column. Surface lake water was pumped through the incubator, and fluorescent lights were used as the light source. The samples were incubated for 3 to 4 hours after which they were filtered through 47-mm HA Millipore filters. The filters were mounted with rubber cement on 52-mm-diameter aluminum planchets and stored for counting. A Low Beta Beckman Planchet Counter was used for counting. Efficiency of this counter and the absolute activity of ^{14}C was determined with a Nuclear Chicago Liquid Scintillation Counter (Wolfe and Schelske, 1967).

Alkalinity was determined from pH measurement on 20-ml samples that were added to 4 ml of 0.01N HCl. Measurements were made only on samples from 1 and 5 m where ^{14}C productivity was measured.

A Technicon AutoAnalyzer II basic Dual-Channel System was equipped to measure four nutrients -- nitrate plus nitrite nitrogen, ammonia nitrogen, soluble reactive silica, and chloride, on shipboard using unfrozen samples (Figure 3.3). Samples for total phosphorus, total soluble phosphorus, and sulfate were frozen and returned to Ann Arbor for analyses. Methods for chemical analyses have been used previously (Schelske et al., 1976) and are described by Davis and Simmons (1979).

Nitrate was reduced to nitrite with a copper-hydrazine solution at 54°C. The nitrite produced and the nitrite initially present in the sample were then determined by a diazotization-coupling reaction using sulfanilamide and N-1-naphthyl-ethylene diamine. The resulting red-violet colored complex was measured at 520 mμ (Kamphake et al., 1967). Nitrite was not analyzed separately, as quantitatively insignificant values would be expected in non-polluted oxygenated waters.

Ammonia was oxidized to nitrous acid by hypochlorite, which reacts with phenol to give a blue color. The reaction was catalyzed by nitro-prusside and buffered by EDTA. The color produced was measured at 630 mμ. A special sampling chamber was used in which acid-scrubbed air was constantly purged to

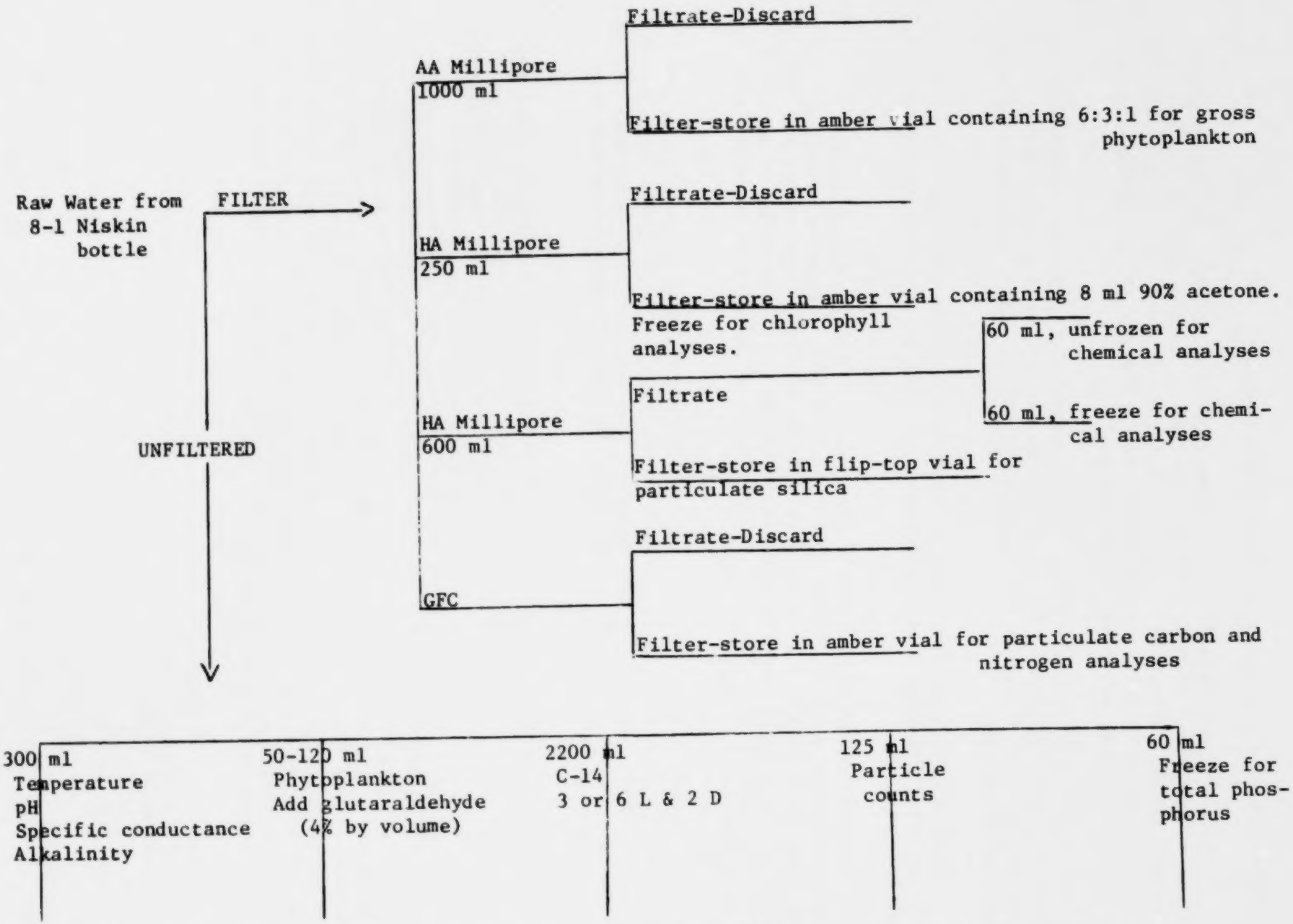

Raw Water from
8-1 Niskin
bottle
FILTER
UNFILTERED
AA Millipore
1000 ml
Filtrate-Discard
Filter-store in amber vial containing 6:3:1 for gross phytoplankton
HA Millipore
250 ml
Filtrate-Discard
Filter-store in amber vial containing 8 ml 90% acetone. Freeze for chlorophyll analyses.
HA Millipore
600 ml
Filtrate
60 ml, unfrozen for chemical analyses
60 ml, freeze for chemical analyses
Filter-store in flip-top vial for particulate silica
GFC
Filtrate-Discard
Filter-store in amber vial for particulate carbon and nitrogen analyses
300 ml
Temperature
pH
Specific conductance
Alkalinity
50-120 ml
Phytoplankton
Add glutaraldehyde
(4% by volume)
2200 ml
C-14
3 or 6 L & 2 D
125 ml
Particle
counts
60 ml
Freeze for
total phosphorus

Figure 3.3. Flow chart illustrating sample processing for study of southern Lake Huron, 1974.

minimize ammonia contamination from the atmosphere.

Silica was determined by the heteropoly-blue method. In this method, silica is complexed with acidified molybdate to form a silicomolybdate complex that is reduced to an intense heteropoly blue. Oxalic acid was added with ascorbic acid prior to the reduction to destroy any phosphomolybdate. The color produced was measured at 630 mμ.

Chloride was determined from its reaction with mercuric thiocyanate that forms mercuric chloride. The released thiocyanate reacts with ferric ammonium sulfate to form a red complex, $Fe(SCN)_3$. The resulting color was measured at 480 mμ.

Chemical analyses for total phosphorus, total soluble phosphorus, and sulfate were performed in the laboratory on thawed samples with the Technicon AutoAnalyzer.

Samples for total phosphorus and total soluble phosphorus were concentrated by evaporation and then digested with potassium persulfate for one and a half hours in an oven at 110°C, as modified from Menzel and Corwin (1965). The samples were then treated with an acidic solution of ammonium molybdate to give phosphomolybdate that was then reduced by ascorbic acid to give a blue color. This was measured at 630 mμ.

An automated turbidimetric method was used for the determination of sulfate. The turbidity produced by the reaction of $BaCl_2$ in HCl with sulfate was measured at 420 mμ. An NH_4-OH-EDTA rinse was used to prevent the coating of the $BaSO_4$ precipitate on the walls of the manifold system and the flow cells (Santiago et al., 1975).

Samples for chlorophyll a (250 ml) were filtered on 47-mm HA Millipore filters that were then extracted in 90 percent acetone buffered with magnesium carbonate. Samples were stored in amber vials in the dark at 0°C for a minimum of 12 hours. On the earlier cruises, some chlorophyll determinations were made on the ship. Otherwise, they were done in our laboratory in Ann Arbor. Samples were centrifuged, and then 5 ml were transferred to sample cuvettes and read in a modified Turner Model 111 fluorometer. The samples were subsequently acidified with 50 percent V/V HCl and read in the fluorometer for phaeopigment determination (Strickland and Parsons, 1968). All results were corrected for phaeophytin. The phaeophytin fraction generally represented a small proportion of the chlorophyll a, so possible errors resulting from the addition of excess amounts of hydrochloric acid (Riemann, 1978) would probably be small.

There are limitations to our experimental design in addition to the changing station pattern and to omitting stations on the first three cruises and on cruise 7 (Table 3.1). One limitation was that 5 days were required to sample the 44 stations, or under normal conditions, about 100 hours elapsed from the time the first station was sampled until the last station was sampled. A second limitation was that our sampling design included only the southern part of the lake so that no data are available for northern Lake Huron or only limited data that were collected in 1974 by the Canada Centre for Inland Waters. Finally, our sampling program did not include stations from the inner part of Saginaw Bay, but three transects of stations (Stations 36 to 59) did provide good coverage of outer Saginaw Bay. Saginaw Bay, however, was sampled rather intensively by Smith et al. (1977) at the same time as our 1974 studies. Combined, our study and Smith's provide good coverage of Saginaw Bay that can be used to verify the extreme range of environmental conditions and determine the exchange of materials between the two water masses.

In interpreting the data, the reader should be aware of the limitations outlined above. Lack of synoptic coverage and the fact that adjacent stations may have been sampled on different days may in some cases make the interpretation of data rather difficult. Persons working with the data, which are on file in STORET, should be aware of these limitations and if their particular applications warrant, should determine when data were collected.

A final caution to the user of the data, particularly those who might use the data filed in STORET. The quality of the data is not uniform among various variables or within variables among the different cruises. In the text, we have pointed out inconsistencies; for example, many of the pH measurements were not considered reliable and have either been omitted or given little weight in our discussion. Also, in our discussion of the data we have adjusted our interpretations to reflect the quality of data where such adjustments are needed.

THERMAL CONDITIONS

The eight cruises on Lake Huron can be divided into four periods, according to thermal characteristics: thermal bar, spring warming, summer stratification, and autumnal cooling. The presentation of physical-chemical data is organized according to these thermal periods (Table 3.3).

Thermal Bar

On the first two cruises conducted in April and May, the thermal bar was obvious over the study area with water temperatures being >4°C offshore and <4°C nearshore (Figures 3.4a and b). The major differences in surface water temperatures between the two cruises were that the 4°C isotherm was farther offshore during the May cruise (Figure 3.4b) than during the first cruise (Figure 3.4a), and the nearshore area of the lake encompassed by the 8°C isotherm was much larger on the second cruise, extending all along the east and west shores of the lake and into Saginaw Bay.

As would be expected, the area of the lake that was <4°C was related to the depth profiles in the lake, with the shallower areas warming faster than the deeper areas. As a consequence, the area with water temperatures >4°C was larger in the shallow southern part of the study area than in the deeper northern part.

TABLE 3.3. DATES AND THERMAL PERIODS OF CRUISES
ON SOUTHERN LAKE HURON, 1974

Cruise number	Time of cruise	Thermal period
1	April 28–May 3	
2	May 14-17	Thermal bar
3	June 4-8	
4	June 17-21	Spring warming
5	July 17-22	
6	August 26-31	Summer stratification
7	October 8-12	
8	November 10-14	Autumnal cooling

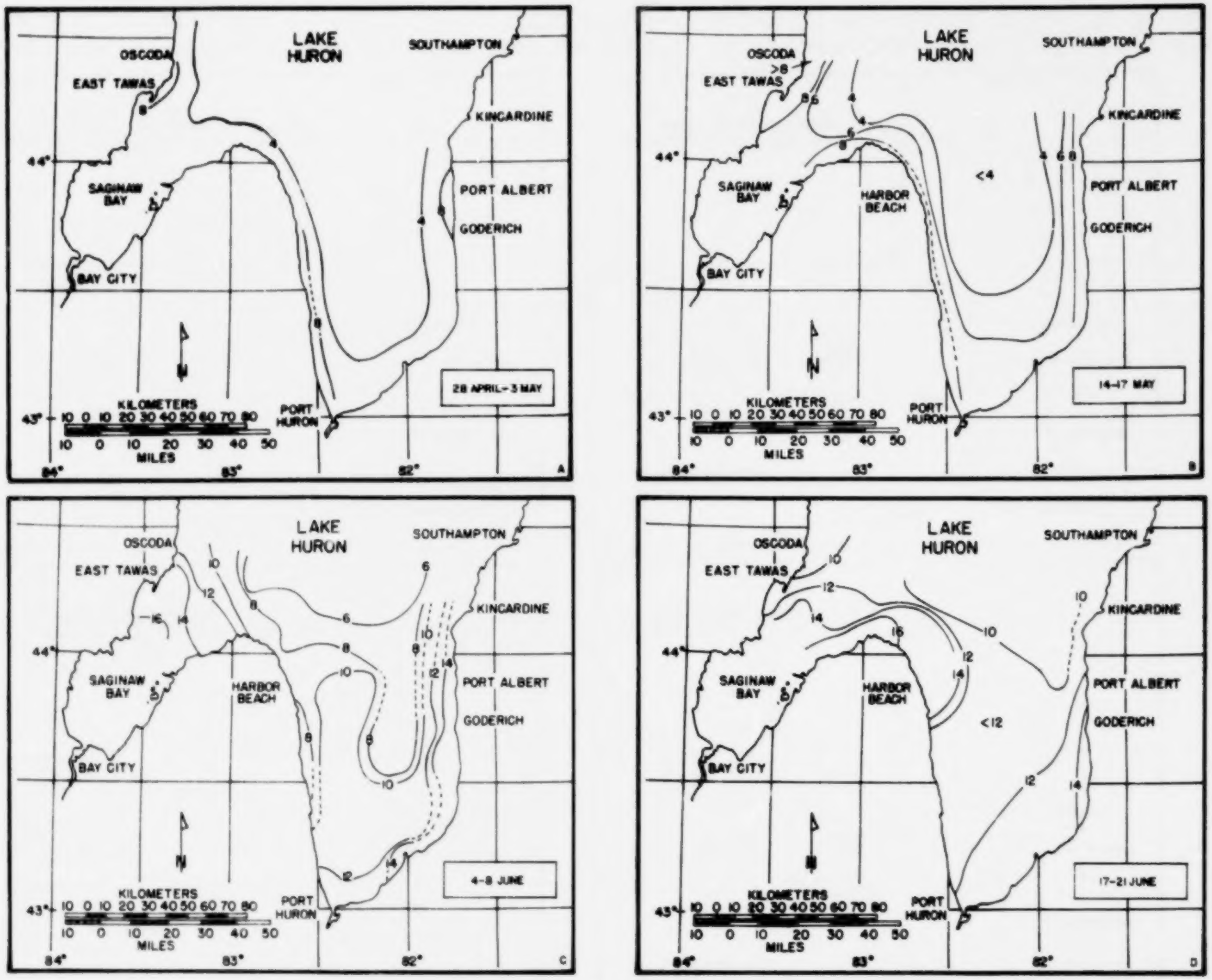
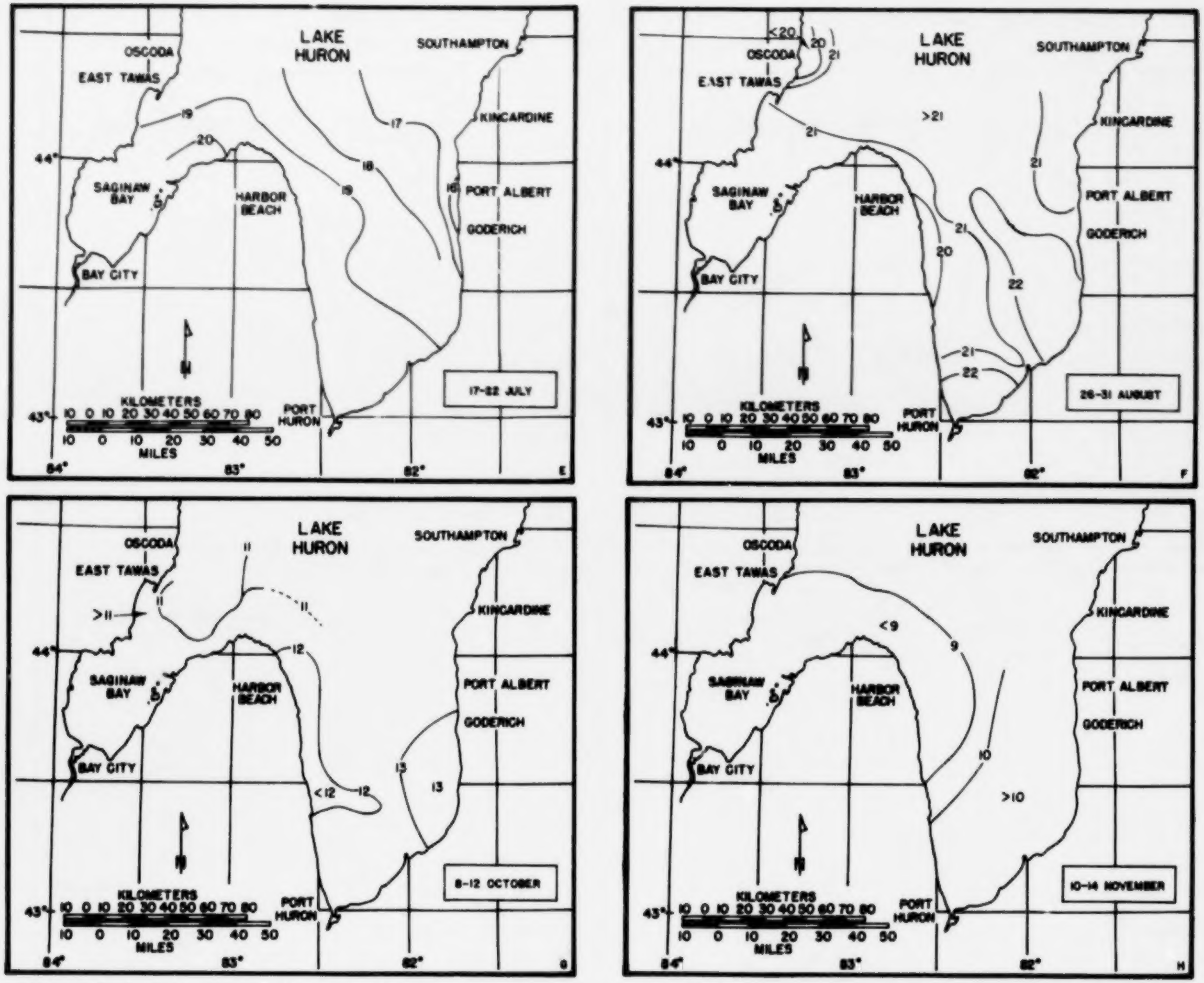

LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
N
44°
43°
84°
83°
82°
28 APRIL–3 MAY
14–17 MAY
4–8 JUNE
17–21 JUNE
>8
<4
<12
4
6
8
10
12
14
16
A
B
C
D

Figure 3.4. Surface water temperature (°C) in southern Lake Huron, 1974. (a) Cruise 1, April 28-May 3; (b) Cruise 2, May 14-17; (c) Cruise 3, June 4-8; (d) Cruise 4, June 17-21. (continued).



LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
17-22 JULY
19
20
17
18
19
16
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
43°
44°
84°
83°
82°
E
26-31 AUGUST
<20
20
21
>21
21
21
20
22
21
21
22
F
8-12 OCTOBER
>11
11
11
11
12
<12
12
13
13
G
10-14 NOVEMBER
<9
9
10
>10
H

Figure 3.4 (continued). Surface water temperature (°C) in southern Lake Huron, 1974. (e) Cruise 5, July 17-22; (f) Cruise 6, August 26-31; (g) Cruise 7, October 8-12; and (h) Cruise 8, November 10-14.

Spring Warming

By mid-June, the thermal bar was no longer present. The retardation of warming was still obvious, however, in the northern and deeper parts of the study area where surface water temperatures were <6°C during the first week in June (Figure 3.4c) and <10°C by mid-June (Figure 3.4d). In contrast, nearshore temperatures were 4-8C° warmer than the offshore temperatures on both cruises.

On the two June cruises, strong vertical thermal stratification was evident only in nearshore areas and in Saginaw Bay. Considerable warming of surface waters occurred in the 2 weeks between the two June cruises, so that by the third week in June, water temperatures south of a line between Harbor Beach and Goderich were about 12°C or greater (Figure 3.4d).

Summer Stratification

Strong vertical thermal stratification developed after the second June cruise and was present during the July and August cruises. In July, surface water temperatures ranged from 17-19°C in the open lake with a gradient of increasing temperature from the northeast to the southwest (Figure 3.4e). The pattern of isotherms observed may have been caused by transport of cold water from the north along the east shore of Lake Huron or by weak upwelling along the eastern shore in the vicinity of Port Albert and Kincardine.

Maximum temperatures observed during the study occurred during the last week of August when surface water temperatures ranged from 20 to 22°C. The warmest temperatures were present in the southern part of the lake near the outflow to the St. Clair River and along the eastern shore (Figure 3.4f).

Autumnal Cooling

By early October, the surface waters of the lake had cooled from the 20-22°C range observed in late August to 11-13°C. The warmest temperatures were found along the east coast south of Goderich (Figure 3.4g). Surface temperatures along the west coast were cooler than in the open lake, and as a consequence, surface temperature decreased generally from east to west.

In November, the lake had cooled so that the surface waters ranged from 9-11°C with temperatures >10°C being present only in the southeastern part of the lake (Figure 3.4h). The effect of depth on the rate of cooling was apparent from examination of the data collected because colder water (<9°C) was found in Saginaw Bay, which is shallow, and warmer water was present in the deeper main lake. Warmer waters at mid-lake may reflect, in part, transport of waters from the northern deeper parts of the lake, which because of a larger mass, cool at a slower rate than shallower waters.

CHLORIDE

In contrast to the major plant nutrients, chloride, being a conservative substance, would not be expected to vary seasonally. Variations in chloride concentration seasonally and spatially on any given cruise, therefore, can be related to inputs primarily from shoreline sources. In southern Lake Huron, the two major shoreline sources are Saginaw Bay on the United States side of the lake and the area near Goderich on the Canadian side of the lake.

Thermal Bar

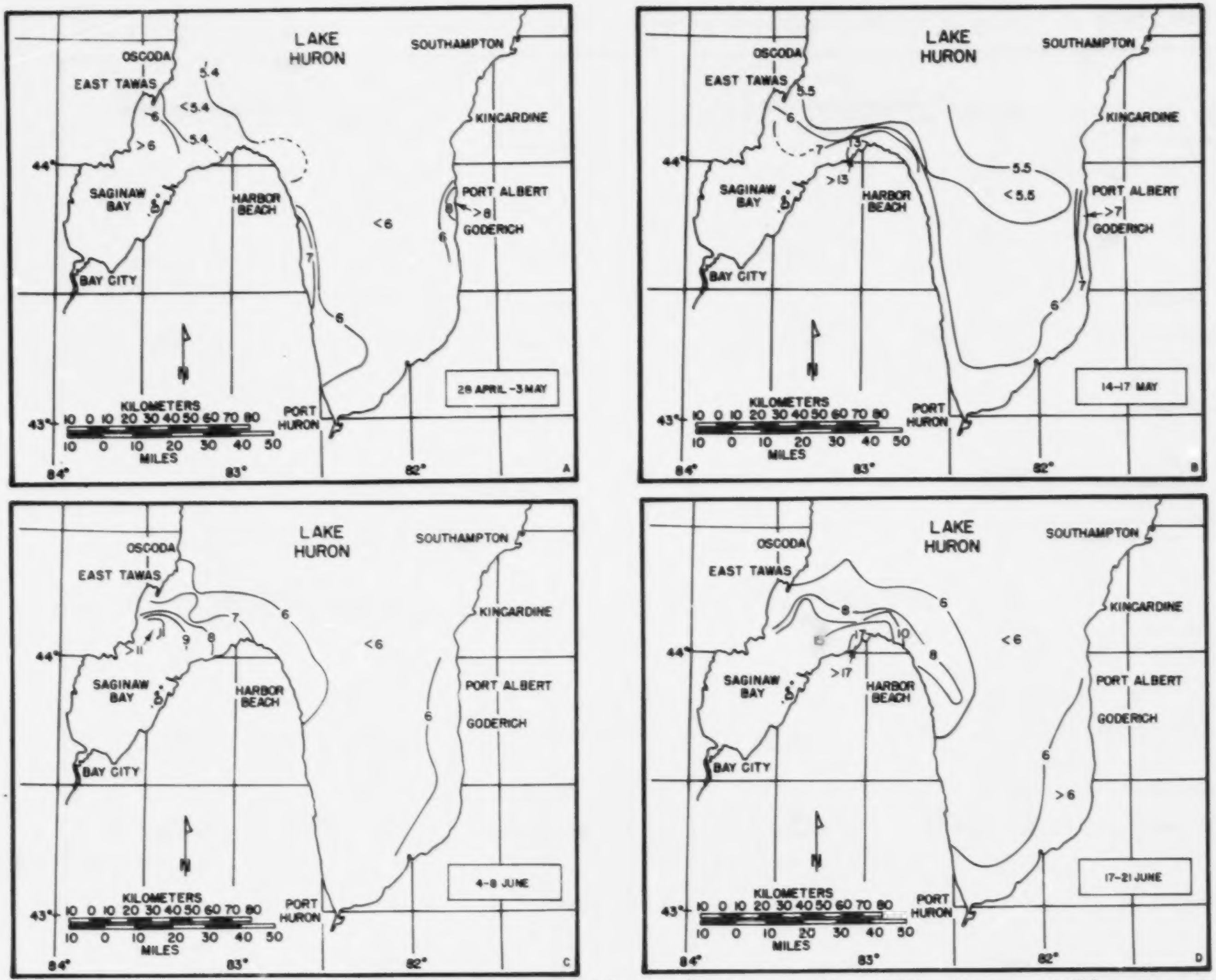
During the first cruise of the thermal bar period, chloride concentrations were quite uniform over the study area, with concentrations in Saginaw Bay being only slightly greater than in the open lake (Figure 3.5a). Other areas of "high" chloride concentrations along the western shore of the lake south of Harbor Beach and on the eastern shore of the lake near Goderich were limited in extent with chloride concentrations ranging to 8 mg/l near Goderich, about 2 mg/l greater than the open lake. Concentrations in outer Saginaw Bay were only 6 mg/l, indicating that the effect of the thermal bar on water transport was quite pronounced, holding water with larger concentrations within the area of Saginaw Bay, which was not sampled. By the second cruise, however, water with higher chloride concentration was present in the sampling area, as indicated by concentrations of 13 mg/l and by the 7-mg/l isopleth that was found in Saginaw Bay (Figure 3.5b). The only other area of relatively high concentration was off Goderich where the water contained 7 mg/l of chloride. Mid-lake concentrations of chloride on the second cruise did not change from the first cruise, being 5.5 mg/l.

Spring Warming

Chloride distributions during the spring warming cruises were characterized by two features not found during the thermal bar period. First, water with relatively high chloride concentrations was found across the mouth of Saginaw Bay (Figures 3.5c and d), and second, the high chloride concentrations along the east shore near Goderich had disappeared, presumably because of the breakdown of the thermal bar. However, water along the eastern shore did have chloride concentrations >6 mg/l, a concentration slightly greater than the open lake.

Chloride concentrations >11 mg/l were found in early June along the northern part of outer Saginaw Bay (Figure 3.5c). Chloride isopleths at this time indicated that water was being transported out of the bay along the northern shore, but on the second cruise in June, high chloride concentrations, >17 mg/l, were found along the southern shore near the thumb (Figure 3.5d), indicating that water was being transported into the open lake on the opposite shore.

Mid-lake concentrations on both June cruises were <6 mg/l, or essentially the same as on the first two cruises. Patterns of isopleths on both cruises indicated chloride input from Saginaw Bay to the open lake because concentrations >6 mg/l were found in the area off Harbor Beach. The observed pattern of isopleths is interpreted as being the result of transport of high chloride water from Saginaw Bay, which was mixed and diluted with open lake water of lower chloride concentration, producing water masses offshore from Harbor Beach with chloride concentrations >6 mg/l. There was also some indication of input from the Canadian shore, because on both


LAKE HURON
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SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
5.4
<5.4
>6
<6
6
7
>8
28 APRIL-3 MAY
A
5.5
<5.5
>13
13
>7
14-17 MAY
B
>11
11
9
8
4-8 JUNE
C
>17
17
10
>6
17-21 JUNE
D
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
N
44°
43°
84°
83°
82°

Figure 3.5. Surface concentrations of chloride (mg/l) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).

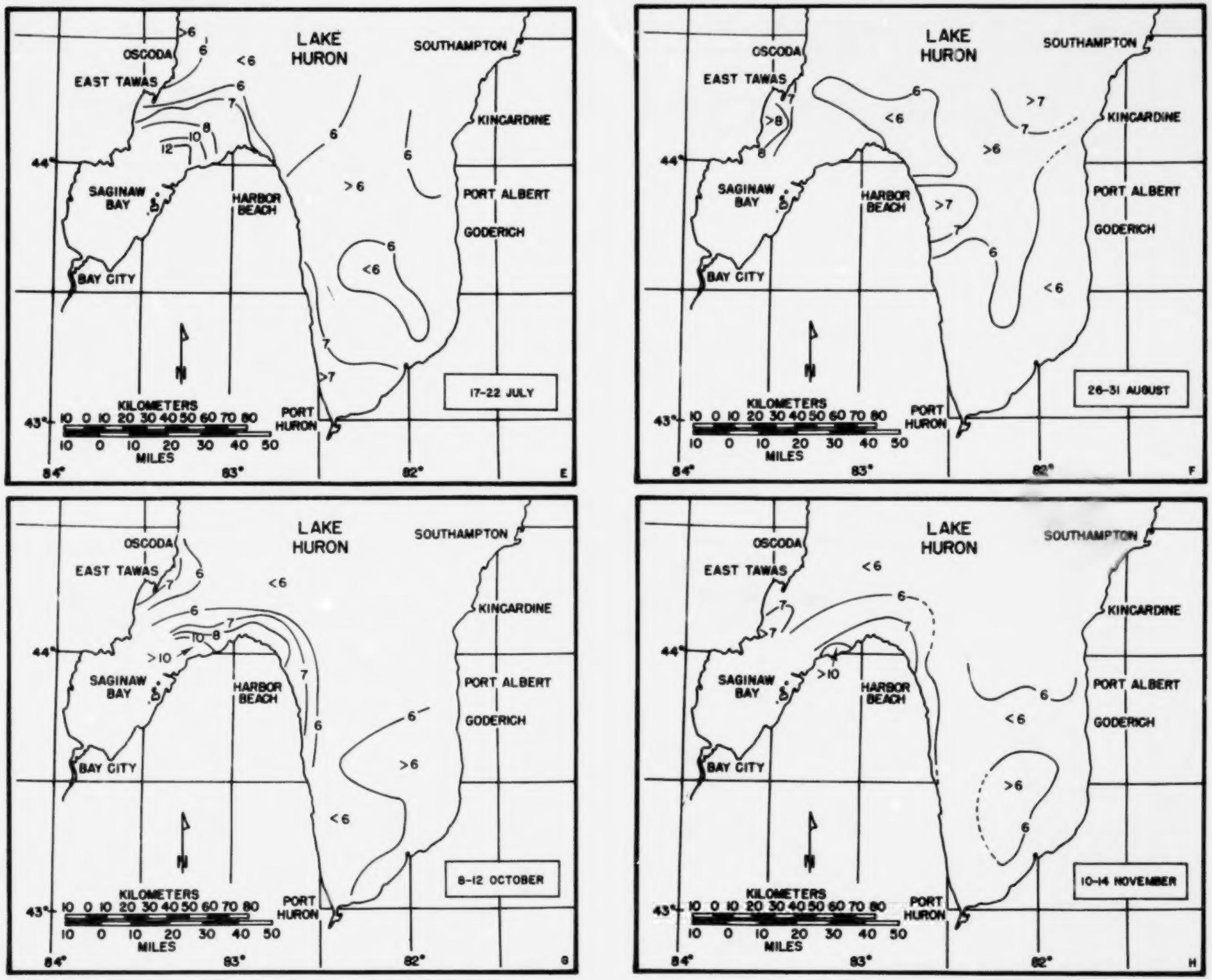

LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
N
44°
43°
84°
83°
82°
17-22 JULY
E
26-31 AUGUST
F
8-12 OCTOBER
G
10-14 NOVEMBER
H
>6
<6
6
7
8
10
12
>7
>8
>10

Figure 3.5 (continued). Surface concentrations of chloride (mg/l) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

cruises concentrations >6 mg/l were found along the eastern shore of the lake.

Postulating transport of water from Saginaw Bay to the open lake along the northern shore of Saginaw Bay based on chloride concentrations on cruise 3 is also supported by the pattern of temperature isotherms (Figure 3.4c); likewise, postulating easterly and southerly transport of high chloride water along the southern shore of Saginaw Bay during cruise 4 is also supported by the pattern of isotherms (Figure 3.4d).

Summer Stratification

On the July cruise, high chloride water was most pronounced in the southern part of Saginaw Bay (Figure 3.5e). This water appears to have been transported from inner Saginaw Bay toward the open lake in a northeasterly direction. The transport of high chloride water was accompanied by an intrusion of low chloride water, <6 mg/l, along the northern shore of the bay in the vicinity of East Tawas. Water with elevated chloride concentrations extended into the lake to the northeast rather than being confined to the nearshore area east and south of the thumb.

On the August cruise, chloride concentrations in outer Saginaw Bay were much less than in July, but the area with the greatest concentration was in Saginaw Bay along the northern shore near Tawas Bay where concentrations exceeded 8 mg/l only in a limited area (Figure 3.5f). Concentrations in most of outer Saginaw Bay were <7 mg/l, which suggests that at least in the area sampled, Saginaw Bay water had been displaced by intrusions of open lake water.

Main lake concentrations on the July and August cruises ranged from <6 mg/l to 7 mg/l over most of the study area (Figures 3.5e and f). The distribution of chloride on the August cruise indicates extensive horizontal transport and mixing prior to this cruise because chloride concentrations in outer Saginaw Bay were relatively low and because our data show pockets of high chloride water, >7 mg/l, off Harbor Beach and some 100 km east of Saginaw Bay near Kincardine (Figure 3.5f).

The fact that mid-lake chloride concentrations increased to >6 mg/l during the summer stratification period from concentrations <6 mg/l on the previous cruises is interpreted as being the result of inputs from shoreline sources, primarily from Saginaw Bay. Chloride concentrations increased because high chloride water was transported from Saginaw Bay into southern Lake Huron where it was mixed with relatively low chloride water from the northern part of the lake, increasing the concentration of lake water prior to its discharge through the St. Clair River.

Autumnal Cooling

On the two cruises during this period, high chloride water was present only along the southern shore of Saginaw Bay, indicating water from Saginaw Bay was transported out of the bay along the southern shore and into the open lake (Figures 3.5g and h). On both cruises, there was evidence of intrusion of low chloride water, <6 mg/l, into Saginaw Bay from the northeast and extending into the bay to the south of East Tawas. This pattern is much more pronounced on cruise 7, when the <6 mg/l zone extended through the study area, than on cruise 8.

Mid-lake concentrations remained relatively low at approximately 6 mg/l on both cruises. The fact that water with <6 mg/l covered a greater area on cruise 8 (Figure 3.5h) than on cruise 7 (Figure 3.5g) and that concentrations on both cruises were smaller than during summer stratification indicates that Saginaw Bay water was diluted with open-lake water to a greater degree on cruise 8. From October to November, the depth of the epilimnion increased significantly, thereby providing a greater volume in which to dilute high chloride water from Saginaw Bay.

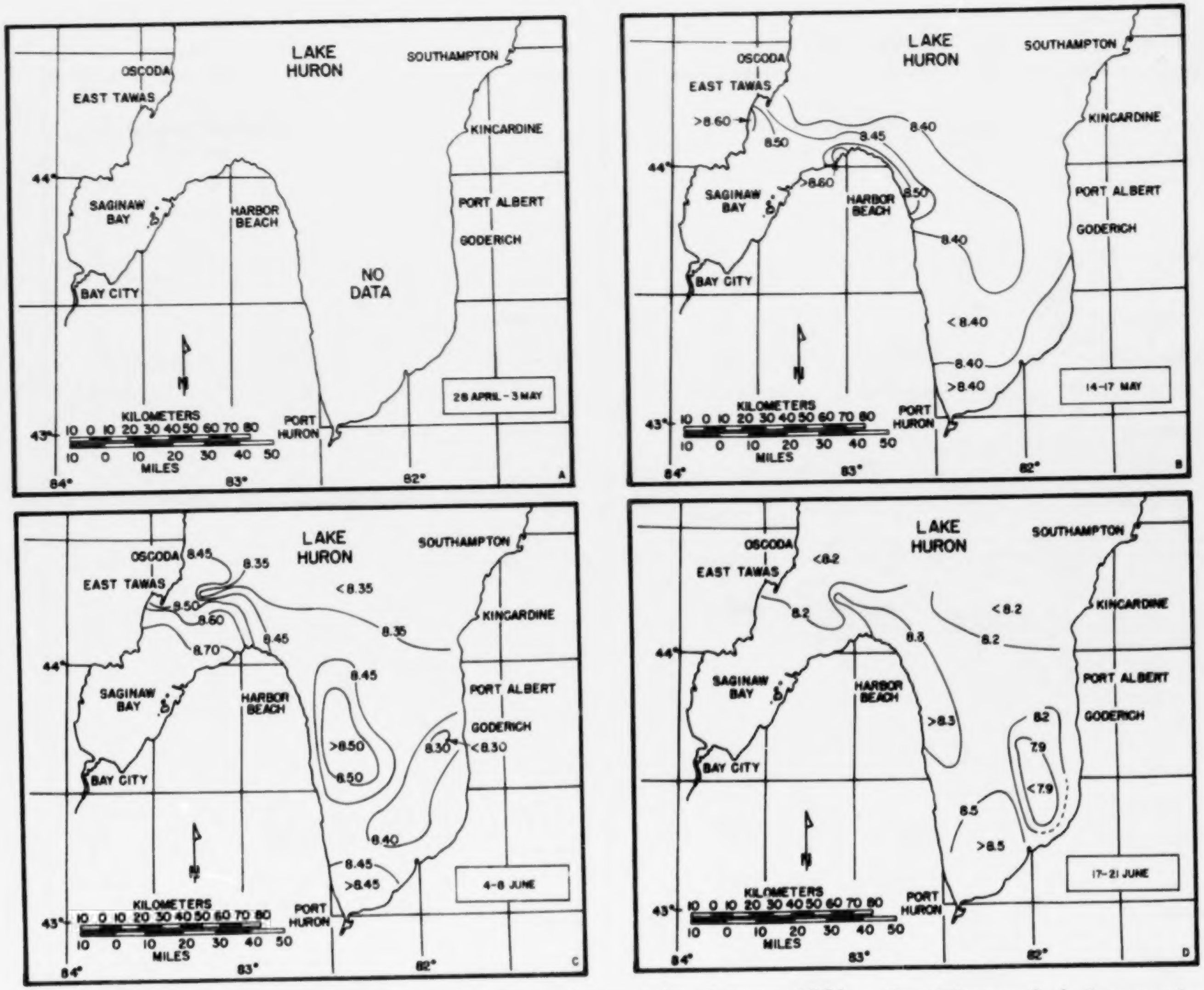
HYDROGEN ION CONCENTRATION

Data for pH are limited; none were obtained on cruise 1 or on cruise 7. In addition, some of the remaining data are difficult to interpret. For example, surface pH, in general, decreased 0.1 or 0.2 units from cruise 3 to cruise 4, indicating first, either a systematic error in measurement techniques, or second, a large change in surface water chemistry. Because these cruises were only two weeks apart, the latter explanation hardly seems logical. However, one explanation for the chemical change might be that, because epilimnetic depth increased between cruise 3 and cruises 4 and 5, mixing of deep water with low pH with surface water of greater pH reduced the epilimnetic pH values between the two cruises.

Another interesting aspect of the data is the low mid-lake pH values on cruises 4 and 5. These values taken in mid-June and mid-July were lower at mid-lake than the values obtained on cruise 3 in early June, indicating a decrease in pH (Fig. 3.6). Sufficient time elapsed between the July and June cruises so that advection of water from the north or epilimnetic entrainment of deep water may be plausible explanations for the decrease in pH. The most interesting feature of the pH data for cruise 5, however, is seen on examination of vertical profiles. At stations where surface pH values ranged from 8.3-8.4, a subsurface maximum in pH can be found. In some cases, the value of this subsurface maximum, usually found at 15-25 or 30 m, is about 8.5. One would have to interpret this increase in pH as resulting either from increased photosynthetic activity at depth or to high pH water that originally was present on the surface and had sunk to thermocline depths as it was being transported within the lake. This feature of maximum pH at thermocline depths also persists to a limited extent in the data obtained on cruise 6 in the latter part of August.

Thermal Bar

On the second cruise when the thermal bar was present, there was little definition in the structure of pH in the surface waters (Figure 3.6b). The pH was >8.4 in Saginaw Bay and around the tip of the thumb, but in most of the lake it was very close to 8.4. Areas with high pH were on the landward side of the thermal bar and were found both on the north and south shores of Saginaw Bay.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PORT ALBERT
GODERICH
SAGINAW BAY
HARBOR BEACH
BAY CITY
PORT HURON
NO DATA
28 APRIL - 3 MAY
A
>8.60
8.50
8.45
8.40
>8.60
8.50
8.40
<8.40
8.40
>8.40
14-17 MAY
B
8.45
8.35
<8.35
8.50
8.60
8.35
8.70
8.45
8.45
>8.50
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8.30
<8.30
8.40
8.45
>8.45
4-8 JUNE
C
<8.2
8.2
<8.2
8.3
8.2
>8.3
8.2
7.9
<7.9
8.5
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17-21 JUNE
D
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
44°
43°
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83°
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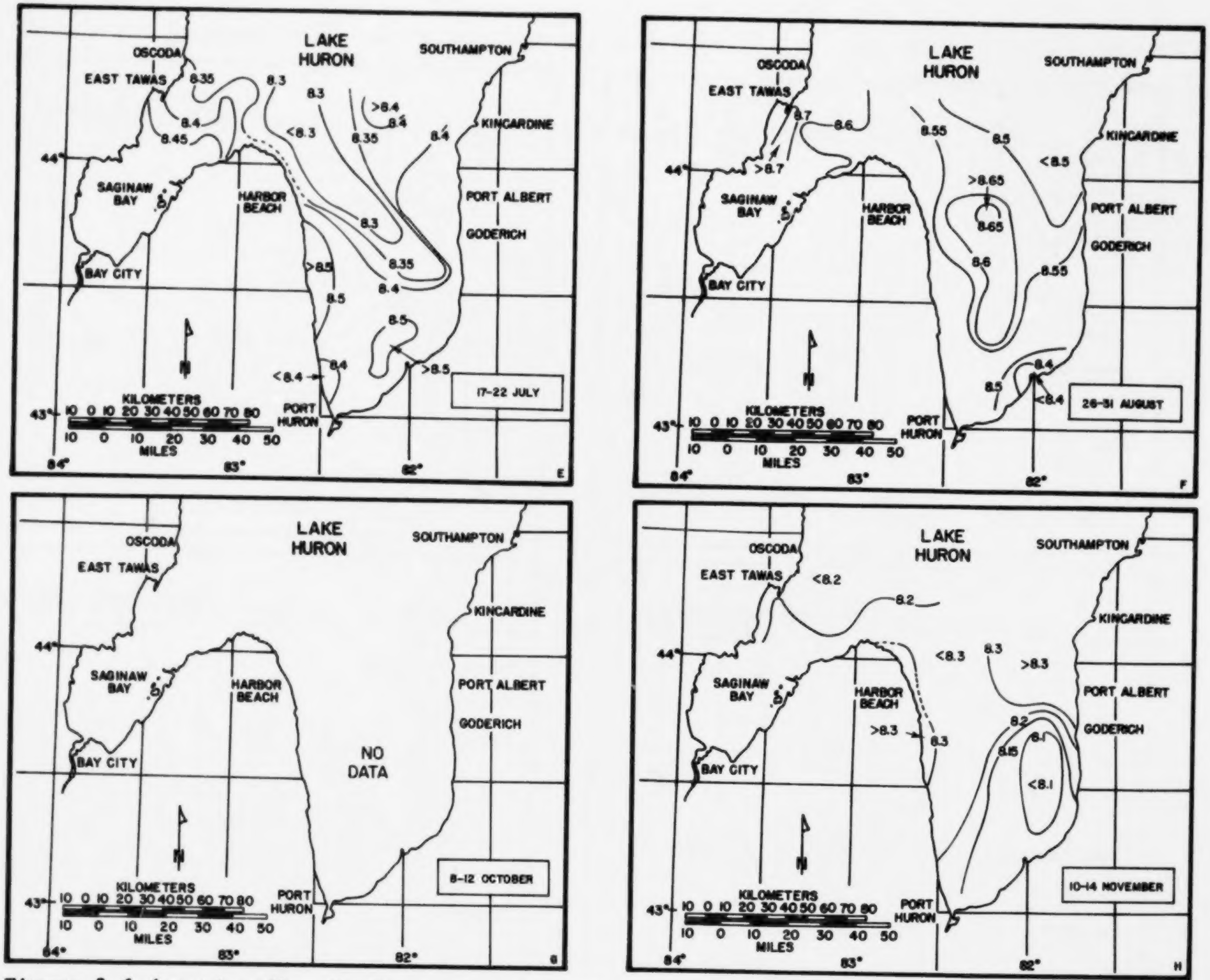
Figure 3.6. Surface values for pH in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).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17-22 JULY
E
8.7
>8.7
8.6
8.55
8.5
<8.5
>8.65
8.65
8.6
8.55
8.4
<8.4
26-31 AUGUST
F
NO DATA
8-12 OCTOBER
G
<8.2
8.2
<8.3
8.3
>8.3
>8.3
8.2
8.15
8.1
<8.1
10-14 NOVEMBER
H

Figure 3.6 (continued). Surface values for pH in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

Spring Warming

On the two cruises in June, there are two major points related to pH. First, there is the large differences between pH values for the two cruises; much higher values for pH were found, as discussed above, on the early June cruise then on the cruise conducted 2 weeks later. The second feature is the very large values for pH found to the south of Saginaw Bay where pH was >8.6 and in a limited area represented by two stations where pH was >8.7 (Figure 3.6c). The large values for pH were associated with water temperatures in Saginaw Bay that were 6-10C° greater than in the open lake. In the open lake waters, pH ranged from 8.3 to 8.45. On the second cruise in June, however, pH values were less in the study area, ranging from 7.9 to 8.2, with the exception of a small area near the southern part of the lake where values were >8.5. Possible explanations for these differences were given above.

Summer Stratification

On the first cruise during the summer stratification period, pH varied little over the study area, ranging generally from 8.3 to 8.5 (Figure 3.6e). Higher values were found in Saginaw Bay and along the east and west shores of the lake. Low values in the center of the lake, <8.3 in some cases, were not expected, and explanations have been discussed above.

In the 6 weeks between the two summer stratification cruises, pH increased greatly over a large part of the central area of the lake, being >8.55 and ranging to as high as >8.65 at one station (Figure 3.6). Likewise, in Saginaw Bay, pH was elevated, being >8.6 and ranging to >8.7 at the mouth of the bay. One value, <8.4, was obtained in the southeastern part of the lake. Whether this is a true value or not is questionable.

Autumnal Cooling

In November (the only cruise during autumnal cooling for which pH data are available), pH was much less than during the latter part of summer stratification and ranged generally from 8.2 to 8.3 (Figure 3.6h). Lowest values for pH were found at midlake south of Goderich. The limited data available from our cruise indicate that low pH water, <8.2, was present north of the area that was sampled.

DISSOLVED REACTIVE SILICA

Dissolved reactive silica (silica) varies seasonally, the primary mechanism for its loss being utilization by diatoms. Diatoms have an obligate silica requirement for growth, so the growth of diatoms depletes silica in the surface waters during summer stratification. Silica in the surface waters is replenished during the fall and winter circulation periods when silica from the bottom waters is mixed into the water column. During stratification, bottom waters are enriched with silica released from the sediments and regenerated from diatoms.

Thermal Bar

At the end of April, the horizontal variation in silica over the study area was quite small. The largest concentrations, ranging from 1.7 to 1.8 mg/l, were found at the mid-lake stations (Figure 3.7a). Smaller concentrations, from 1.4 to 1.5 mg/l, were found in the open waters of the southern part of the lake, along the western shore south of Harbor Beach and in a small area of Saginaw Bay. The lowest concentration, 1.0 mg/l, was found along the western shore south of Harbor Beach.

By mid-May, silica concentrations had been reduced to 1.2 mg/l or less over much of the study area, with the exception of a small parcel of water containing 1.4 mg/l at the mouth of Saginaw Bay (Figure 3.7b). Compared with the open lake, silica concentrations were lower in nearshore areas. The area of most extreme silica depletion was in the southern part of Saginaw Bay where silica concentrations were reduced to 0.1 mg/l at one station, probably approaching the minimum level that could be detected by our methodology. On the eastern shore near Goderich, a considerable area had silica concentrations <0.5 mg/l. These areas of reduced silica concentration probably ring the lake inside the thermal bar, but because of the sampling grid employed in this study it was not possible to verify such a structure.

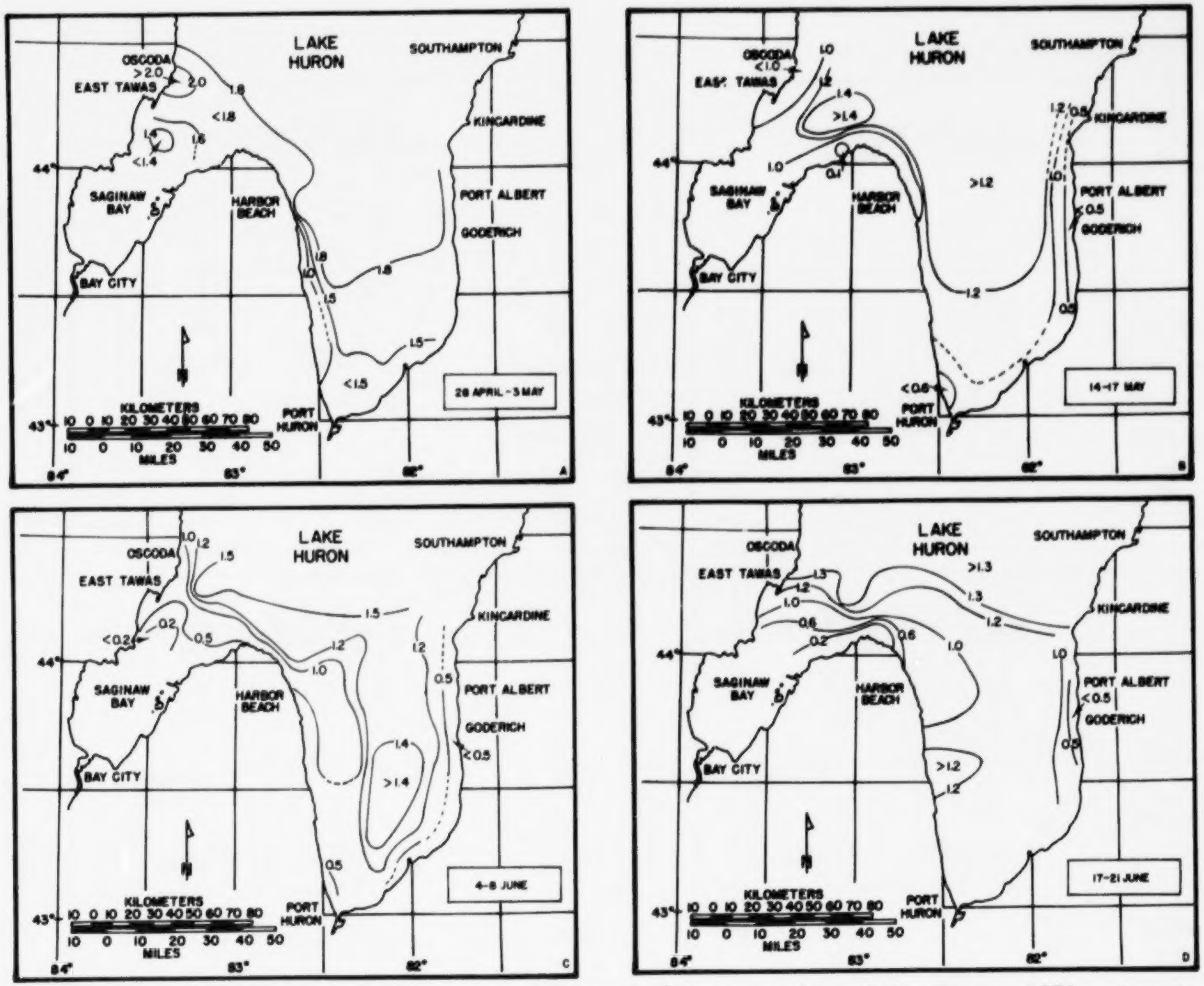
Spring Warming

Two areas had relatively low silica concentrations on both cruises during the period of spring warming. First, along the eastern shore near Goderich, the silica concentration was <0.5 mg/l, and second, in Saginaw Bay, the concentration was lower, <0.2 mg/l (Figures 3.7c and d). On both cruises, there is some indication that the low silica water from Saginaw Bay was either being transported (Figure 3.7c) or had been transported (Figure 3.7d) out of Saginaw Bay along the western shore of the lake, a pattern also suggested by the distribution of chloride. The distribution on cruise 3 also indicates transport of water with 0.2 mg/l to the north alongshore near East Tawas.

Open lake concentrations on the first cruise in June generally ranged from 1.2 to 1.5 mg/l; however, little of the area had concentrations >1.4 mg/l (Figure 3.7c). The 1.5 mg/l isopleth at the northern end of the study area probably indicates the limit of intrusion of northern Lake Huron water with higher silica concentrations than those found in the southern part of the lake. On the second June cruise the relatively high silica concentration water from northern Lake Huron contained 1.3 mg/l (Figure 3.7d). At the time of this cruise in late June, most of the remaining open lake waters had silica concentrations between 1.0 and 1.2 mg/l or less. The reduction in silica concentrations of approximately 0.7 mg/l in the open lake between late April and the latter part of June indicates a relatively rapid growth of diatoms in the surface water.

Summer Stratification

Surface waters on the two cruises during the period of summer stratification were marked by a continued decline in silica concentrations so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PORT ALBERT
GODERICH
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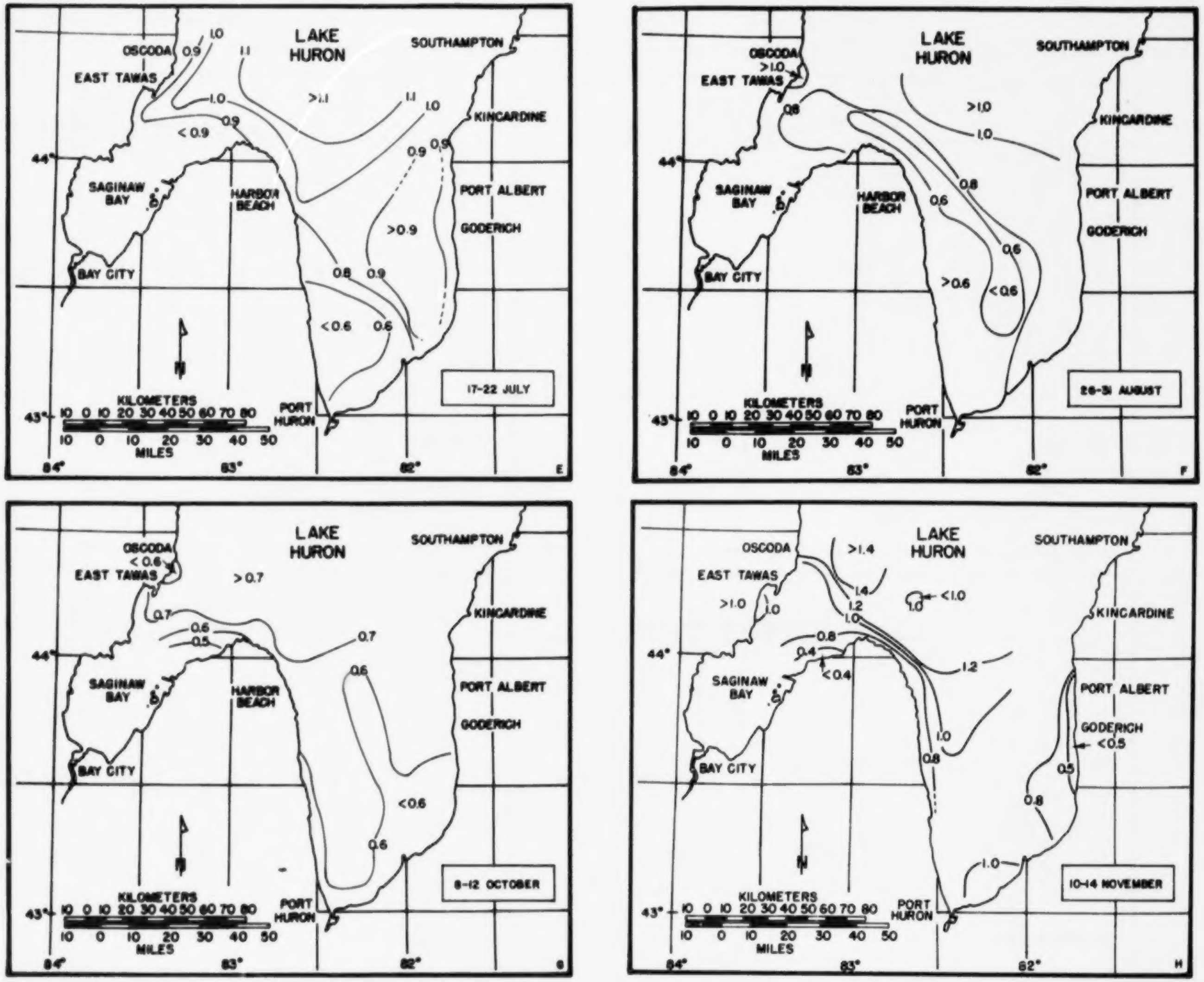
EAST TAWAS
SAGINAW BAY
HARBOR BEACH
BAY CITY
PORT HURON
KILOMETERS
MILES
44°
43°
84°
83°
82°
28 APRIL - 3 MAY
A
14-17 MAY
B
4-8 JUNE
C
17-21 JUNE
D

Figure 3.7. Surface concentrations of silica (mg/1) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).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10 0 10 20 30 40 50 60 70 80
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17-22 JULY
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<0.9
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0.6
26-31 AUGUST
F
>1.0
1.0
0.8
0.6
>0.6
<0.6
8-12 OCTOBER
G
<0.6
>0.7
0.7
0.6
0.5
<0.6
10-14 NOVEMBER
H
>1.4
1.4
1.2
1.0
<1.0
>1.0
0.8
0.4
<0.4
<0.5
0.5

Figure 3.7 (continued). Surface concentrations of silica (mg/l) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

that by the end of August, silica concentrations over much of the study area had been reduced to the range of 0.6 to 0.8 mg/l (Figure 3.7f). Water with higher concentrations found in the northern part of the study area probably delimits the zone in which Saginaw Bay influences open lake chemistry. Higher concentrations to the north result from intrusion of relatively high silica water from the north mixing with low silica water from Saginaw Bay.

On both summer stratification cruises (Figures 3.7e and f), there was relatively little difference in silica concentrations between outer Saginaw Bay and open Lake Huron. As this represents an increase in silica concentration in Saginaw Bay from the period of the thermal bar, these results indicate that there was a relatively large amount of mixing or exchange between outer Saginaw Bay and open Lake Huron between these two periods of the study.

Autumnal Cooling

From late August, the last cruise during the summer stratification period, to early October, the first cruise during the autumnal cooling period, there was a general and continued decrease in silica concentrations in the surface waters, particularly in the northern part of the study area. During early October, most concentrations in the study area were <0.7 mg/l (Figure 3.7g). In the southeastern part of the lake and in Saginaw Bay, areas with <0.6 mg/l were present. In October, there was a north-south gradient in silica concentration that was also present in late August. October concentrations ranged from >0.7 mg/l in the northern part of the study area to <0.6 mg/l in the southern end of the lake.

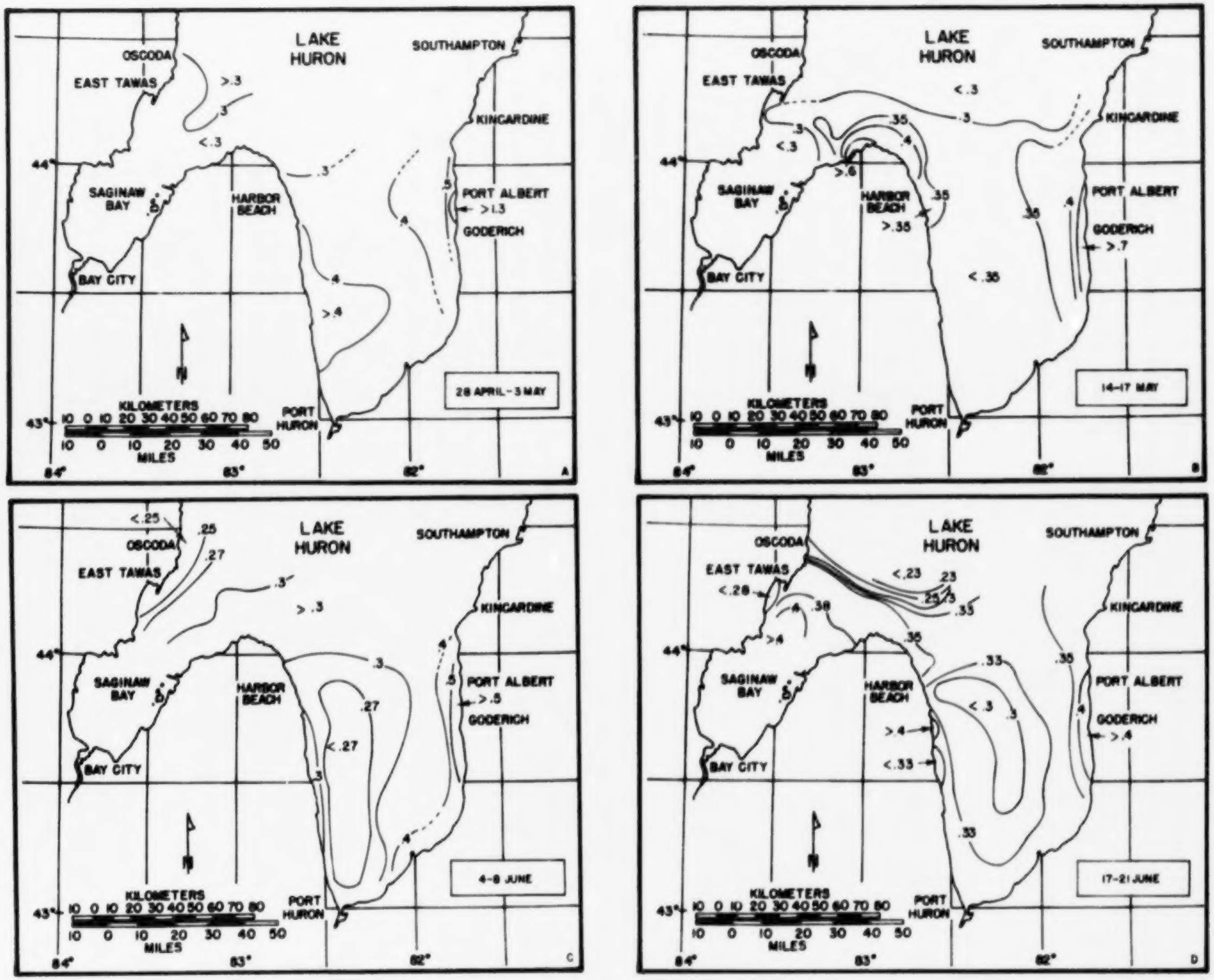
Concentrations of silica in the surface waters in November (Figure 3.7h) increased in relation to concentrations present in October (Figure 3.7g) because of epilimnetic entrainment of subsurface waters relatively rich in silica as the epilimnion cooled and deepened. Concentrations over much of the study area ranged from 0.8 to 1.2 mg/l, except in nearshore areas and in Saginaw Bay where concentrations were 0.8 mg/l and less. The reduced concentrations in the southern part of Saginaw Bay and along the east coast near Goderich were caused by either a period of high diatom growth or the lack of a source of silica-rich waters in these shallow waters, or both.

NITRATE NITROGEN

Nitrate, like silica, varies seasonally as a function of growth of phytoplankton, but unlike silica, its concentration may be reduced by the growth of phytoplankton other than diatoms because all phytoplankton require nitrogen for growth, but not all phytoplankton are diatoms.

Thermal Bar

During the first cruise of the thermal bar period, concentrations of nitrate nitrogen ranged generally from 0.3 to 0.4 mg/l. The major feature that was different was relatively large nitrogen concentrations off Goderich (Figure 3.8a) on the first cruise. These concentrations, exceeding 1.3 mg/l,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>1.3
14-17 MAY
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<.35
>.7
4-8 JUNE
C
<.25
.25
.27
.3
>.3
<.27
.4
.5
>.5
17-21 JUNE
D
<.23
.23
.25
.35
<.28
.38
>.4
.33
<.3
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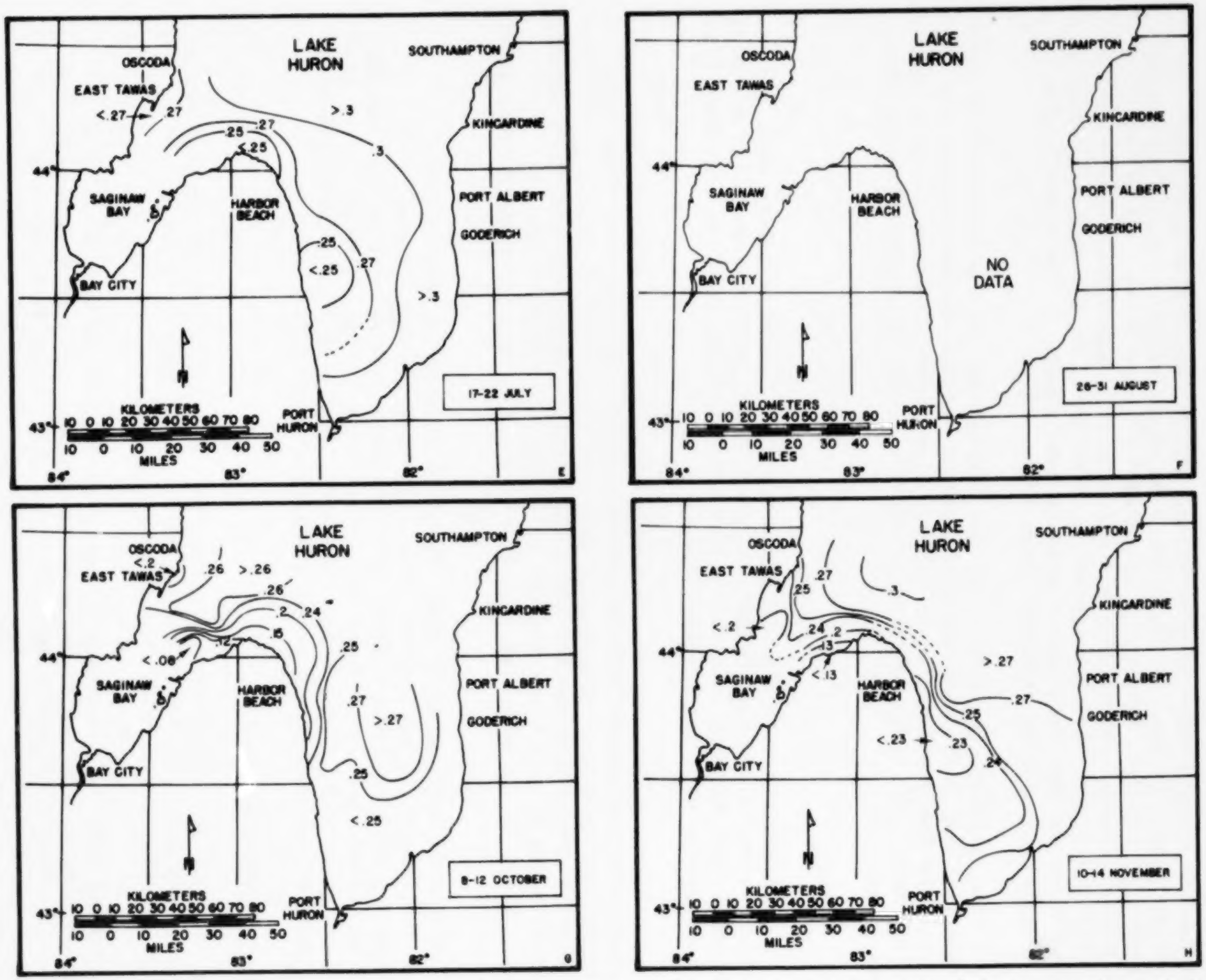
>.4

Figure 3.8. Surface concentrations of nitrate nitrogen (mg/1) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).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KINCARDINE
PORT ALBERT
GODERICH
<.27
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<.25
>.3
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<.25
>.3
17-22 JULY
E
NO DATA
26-31 AUGUST
F
<.2
.26
>.26
.2
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<.08
.12
.15
.25
.27
>.27
<.25
8-12 OCTOBER
G
.3
.24
.13
<.13
>.27
.23
<.23
.24
10-14 NOVEMBER
H
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
43°
44°
84°
83°
82°

Figure 3.8 (continued). Surface concentrations of nitrate nitrogen (mg/l) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

have been traced to the flow of the Maitland River into the lake at Goderich. High, nearshore nitrogen concentrations near Goderich persisted until mid-May. The distribution of large nitrate concentrations near shore has been directly related to the presence of the thermal bar (see Section 7).

On the second cruise of the thermal bar period, nitrate nitrogen concentrations over most of the study area again ranged from 0.3 to 0.4 mg/l, with much of the open lake being <0.35 mg/l (Figure 3.8b). In addition to the area with high nitrate nitrogen off Goderich, there was a small area of relatively high nitrogen concentration, >0.6 mg/l, on the southern shore of Saginaw Bay that may have been caused by land runoff in the general area or may have been caused by transport from Saginaw Bay.

During mid-May, the effects of the thermal bar on the distribution of nitrate nitrogen in Saginaw Bay were evident because concentrations were <0.3 mg/l in Saginaw Bay (Figure 3.8b). This lower concentration probably resulted from utilization of nitrate for the growth of phytoplankton within Saginaw Bay.

Spring Warming

The relatively high nitrate concentrations in the nearshore zone off Goderich, observed during thermal bar conditions, persisted during the spring warming period (Figures 3.8c and d), presumably resulting from continued high nitrate loading from the Maitland River.

On the early June cruise, isopleths of nitrate in Saginaw Bay were parallel, running generally southwest-northeast (Figure 3.8c). This distribution would seem to indicate that low nitrate water is being transported out of Saginaw Bay along the northern shore and that high nitrate water is being transported into the bay along the southern shore. Distributions of chloride and silica also suggest that this type of transport has occurred.

On the second cruise in June, the distribution of nitrate with concentrations >0.35 mg/l corresponds roughly with temperatures >12°C in Saginaw Bay (Figure 3.8d). These data indicate that water from Saginaw Bay is being mixed with water lower in nitrate from the open lake and along the northern shore and is then being transported eastward to the open waters of the lake, at concentrations between 0.33 and 0.35 mg/l.

Summer Stratification

Only one set of data is available from the summer stratification cruises because data from the August cruise could not be used as a result of technical difficulties with the nitrate analysis.

During late July, nitrate nitrogen concentrations were much less variable than during any of the previous cruises and ranged generally from 0.25 to 0.30 mg/l (Figure 3.8e). At this time of the year, nitrate concentrations in lower Saginaw Bay were apparently less than those in the open lake, and the pattern of isopleths indicated that this low nitrate water with concentrations <0.25 mg/1 was being transported out of Saginaw Bay along the southern shore.

Autumnal Cooling

By early October, phytoplankton growth within Saginaw Bay apparently had reduced nitrate concentrations to low levels compared to previous cruises or to the open lake on this cruise. The lowest concentration was <0.08 mg/1 at one station, with a more extensive area of concentrations <0.15 mg/1 being found along the southern shore of Saginaw Bay (Figure 3.8g). The distribution of nitrate on this cruise indicates that Saginaw Bay water was moving out of the bay along the southern shore into the open part of the lake and that open-lake water with relatively high nitrogen concentrations, >0.26 mg/1, was being transported into the outer bay from the northeast.

With the exception of the relatively low nitrate water in Saginaw Bay, concentrations over the rest of the study area were uniform, ranging generally from 0.25 to 0.27 mg/1 (Figure 3.8g).

On the second autumnal cooling cruise, nitrate concentrations within Saginaw Bay were still low, ranging to <0.13 mg/1, but as was observed on the preceding cruise, concentrations over the remainder of the lake were relatively uniform, ranging generally from 0.25 to 0.27 mg/1 (Figure 3.8h).

Differences in nitrate nitrogen concentrations between the southern and northern parts of the lake are evident in data from the November cruise. Concentrations in the southern end of the lake as great as 0.25 mg/1 were found in contrast to concentrations as large as 0.30 mg/1 in the northern part of the study area (Figure 3.8h). Along the western shore and extending into the open part of the lake was a large area with concentrations ranging from <0.23 to 0.25 mg/1 that undoubtedly represents a water mass influenced by inputs from or mixing with water originating in Saginaw Bay.

CHLOROPHYLL a

Chlorophyll a results are of interest because this variable can be measured quite readily on large numbers of samples and can be used as a measure of phytoplankton standing crop. Chlorophyll concentration is a community parameter that provides little insight into the dynamic aspects of phytoplankton productivity because as a static estimate of biomass it does not reflect changes in standing stock or phytoplankton species composition.

Thermal Bar

In late April and early May, chlorophyll a concentrations over much of the study area were relatively constant with concentrations ranging generally from 2 to 3 μg/1. Although low, these concentrations probably represent maximum concentrations obtained in the open waters during the spring bloom. Lin and Schelske (1978) reported a maximum value of 3.0 μg/1 during 1975 from an area near Station 13.

At the end of April, there were two areas with relatively high chlorophyll concentrations. The greatest concentrations existed off Goderich in the area of the high nitrate concentrations where chlorophyll exceeded 16 µg/l and south of Harbor Beach along the western shore where 6 µg/l were found (Figure 3.9a). There also was an area near East Tawas with concentrations exceeding 3 µg/l.

By mid-May, chlorophyll a concentrations in Saginaw Bay had increased to 6 µg/l along the northern shore near East Tawas, and water with 4 µg/l was found along the southern edge of Saginaw Bay extending along the western shore nearly to Harbor Beach (Figure 3.9b). These areas with elevated chlorophyll a concentrations were presumably the result of nutrient input from Saginaw Bay and possibly to the influence of nearshore conditions, because the largest concentrations were located on the landward side of the thermal bar. Along the eastern shore, concentrations >14 µg/l were observed near Goderich in the area of high nitrate concentration.

Spring Warming

On the early June cruise, chlorophyll a concentrations over most of the study area ranged from <1 to 2 µg/l (Figure 3.9c). One station south of Harbor Beach had concentrations >4 µg/l; it was part of an area along the western shore of the lake extending to Saginaw Bay with concentrations >2 µg/l . By the third week in June, concentrations at mid-lake were all <2 µg/l and in some areas had been reduced to <1 µg/l (Figure 3.9d). Relatively large phytoplankton blooms were present in the area near Goderich on the eastern shore and in Saginaw Bay along the southern shore where concentrations ranged from 4 to 6 µg/l.

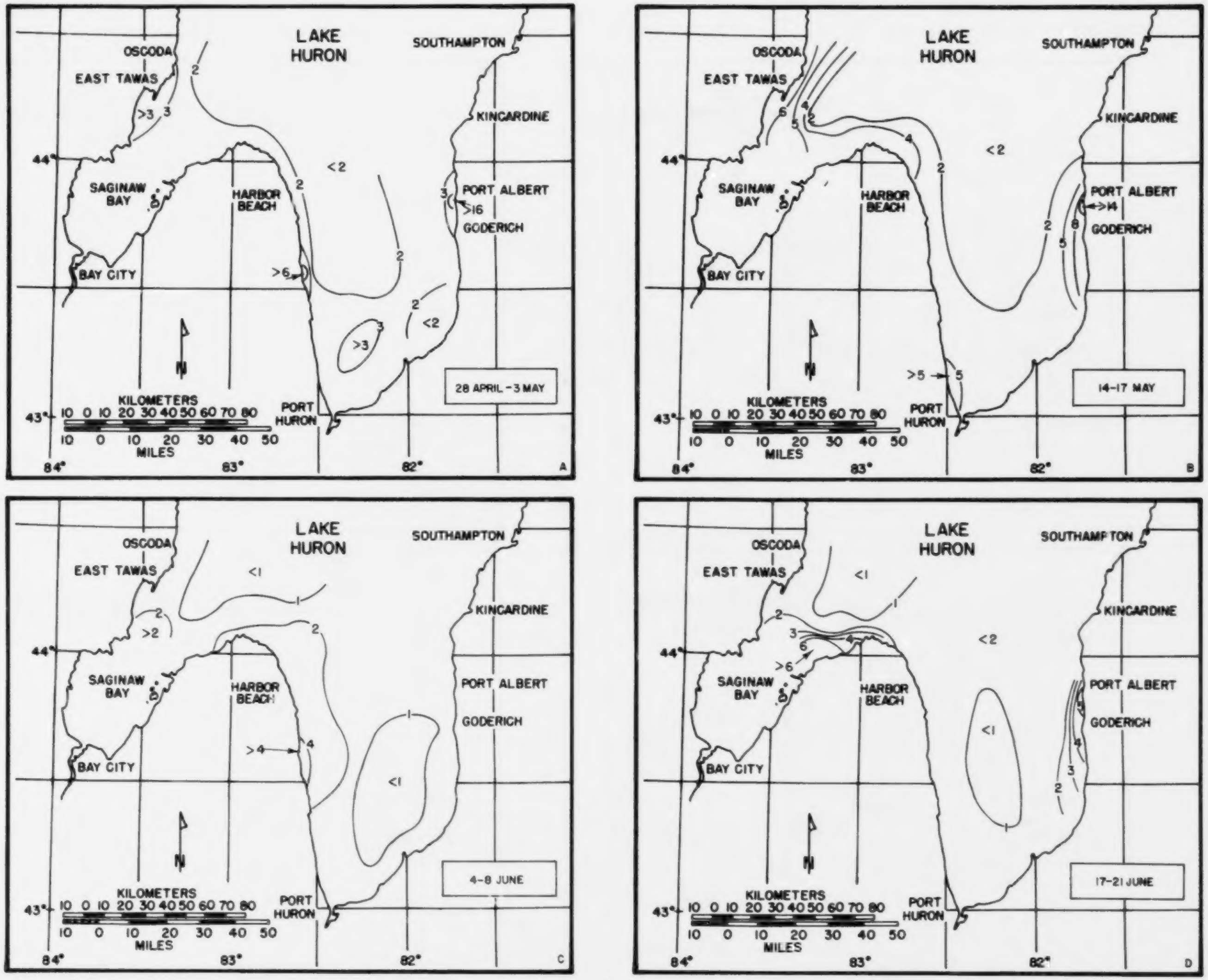
Summer Stratification

During the summer stratification period, open-lake chlorophyll a concentrations were quite low, ranging from <0.4 µg/l to 0.6 µg/l. In July, there was a small area in Saginaw Bay with chorophyll a concentrations >2 µg/l that also was the only area where concentrations exceeded 1 µg/l (Figure 3.9e). This same pattern of low chlorophyll a concentrations existed during the August cruise, and the only areas in which concentrations exceeded 1 µg/l were along the northern shore of Saginaw Bay, extending north of East Tawas where a cruise maximum of 4 µg/l was observed (Figure 3.9f).

Autumnal Cooling

Chlorophyll a concentrations in mid-lake on the October cruise ranged from 1.0 to 1.5 µg/l, which represents the fall bloom as we sampled it (Figure 3.9g). Concentrations >1.5 µg/l were present along the western shore of Saginaw Bay and in Saginaw Bay; however, in most areas, concentrations did not exceed 2 µg/l, with only a small area having concentrations >4 µg/l.

By mid-November, concentrations had decreased to the range of 0.5 to 1.0 µg/l over most of the open lake (Figure 3.9h). Even in Saginaw Bay, concentrations in general were <1.5 µg/l, so that during this cruise, most of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KINCARDINE
PORT ALBERT
GODERICH
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28 APRIL - 3 MAY
A
>3
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>16
>3
14-17 MAY
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4-8 JUNE
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D
>6

Figure 3.9. Surface concentrations of chlorophyll a (μg/1) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).

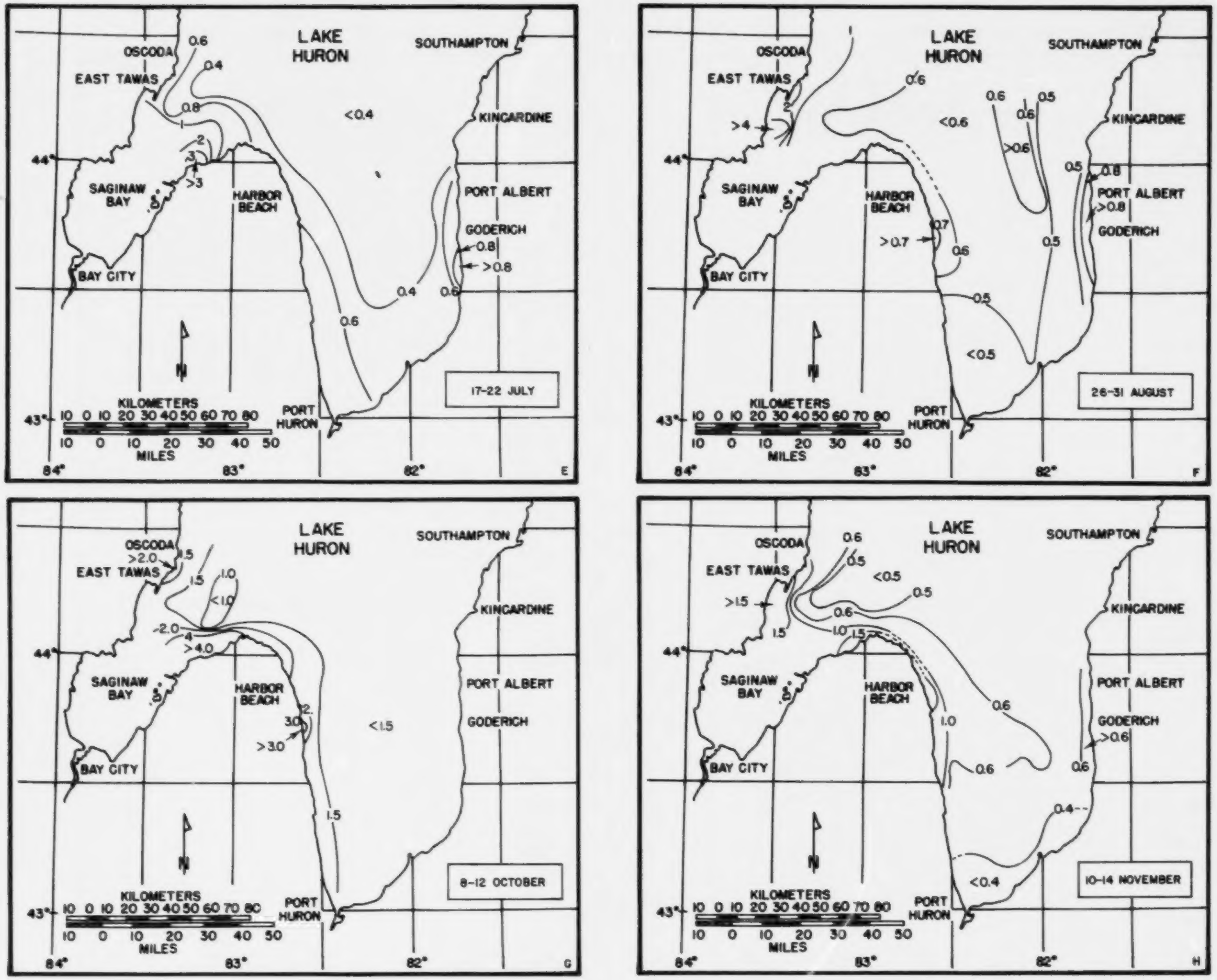

LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
N
84°
83°
82°
43°
44°
17-22 JULY
E
0.6
0.4
0.8
1
2
3
>3
<0.4
0.8
>0.8
0.6
0.4
0.6
26-31 AUGUST
F
2
>4
0.6
<0.6
0.6
0.6
0.5
>0.6
0.5
0.8
>0.8
0.7
>0.7
0.6
0.5
0.5
<0.5
8-12 OCTOBER
G
>2.0
1.5
1.5
1.0
<1.0
2.0
4
>4.0
2
3.0
>3.0
<1.5
1.5
10-14 NOVEMBER
H
0.6
0.5
<0.5
0.5
>1.5
1.5
0.6
1.0
1.5
1.0
0.6
0.6
0.6
>0.6
0.4
<0.4

Figure 3.9 (continued). Surface concentrations of chlorophyll a (μg/l) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

the chlorophyll a concentrations ranged from 0.5 to 1.5 µg/l. Transport of water along the southern shore of Saginaw Bay and then south on the western shore of the lake that was observed on the previous cruise was evident again from chlorophyll a distributions on the November cruise.

SECCHI DISC TRANSPARENCY

Thermal Bar

During the period of thermal bar, the patterns for Secchi disc transparency were essentially the same as those for water temperature, with the greatest transparencies occurring in the middle of the lake on the lakeward side of the thermal bar and lower transparencies being found shoreward of the thermal bar along both shores of the lake and in Saginaw Bay.

In mid-May, the pattern of transparency was related to thermal structure, but Secchi disc transparency in the nearshore zone on both sides of the lake was reduced, being less than it had been on the first cruise (Figure 3.10a and b). This difference was especially pronounced in the area along the eastern shore of the lake.

Spring Warming

In June during the period of spring warming, the inshore-offshore differences in Secchi disc transparency persisted even though the thermal bar was no longer present (Figures 3.10c and d). In June, however, Secchi disc transparency was much less at the mouth of Saginaw Bay than it had been during the cruises in April and May. The area of low transparency water extended south and west of Saginaw Bay along the western shore of Lake Huron.

Transparency over much of the open lake ranged from 6 to 7 m, which was not greatly different than that which had been observed during the previous two cruises during the period of the thermal bar.

Summer Stratification

During July and August, water transparency in Saginaw Bay was much less than in the open waters of the lake (Figure 3.10e and f). Transparency in the open lake increased greatly in comparison to values on the previous cruise. In July the area of low transparency water observed in Saginaw Bay extended farther into the lake than it did in August. Low transparency water was also observed on both cruises in the nearshore area near Goderich.

The open waters of the lake, particularly during July, were very transparent with Secchi disc readings being close to maximum for this study. One value of 16 m and one value of 15.5 m were observed during this cruise. Transparency decreased by the end of August when Secchi disc readings were 10 m or less in the open waters. However, these August readings reflected greater water transparency than had been observed in either the thermal bar or spring warming periods.

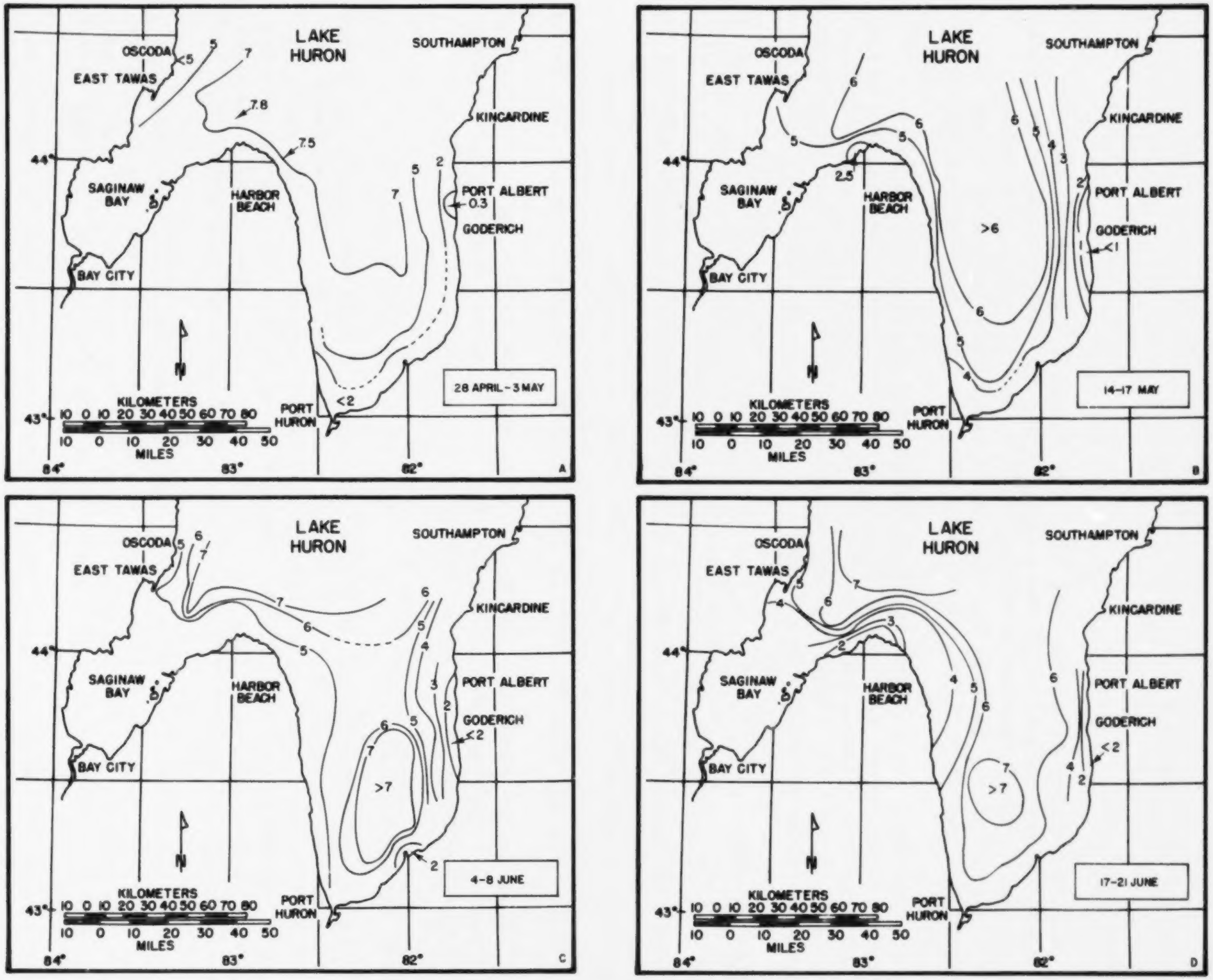
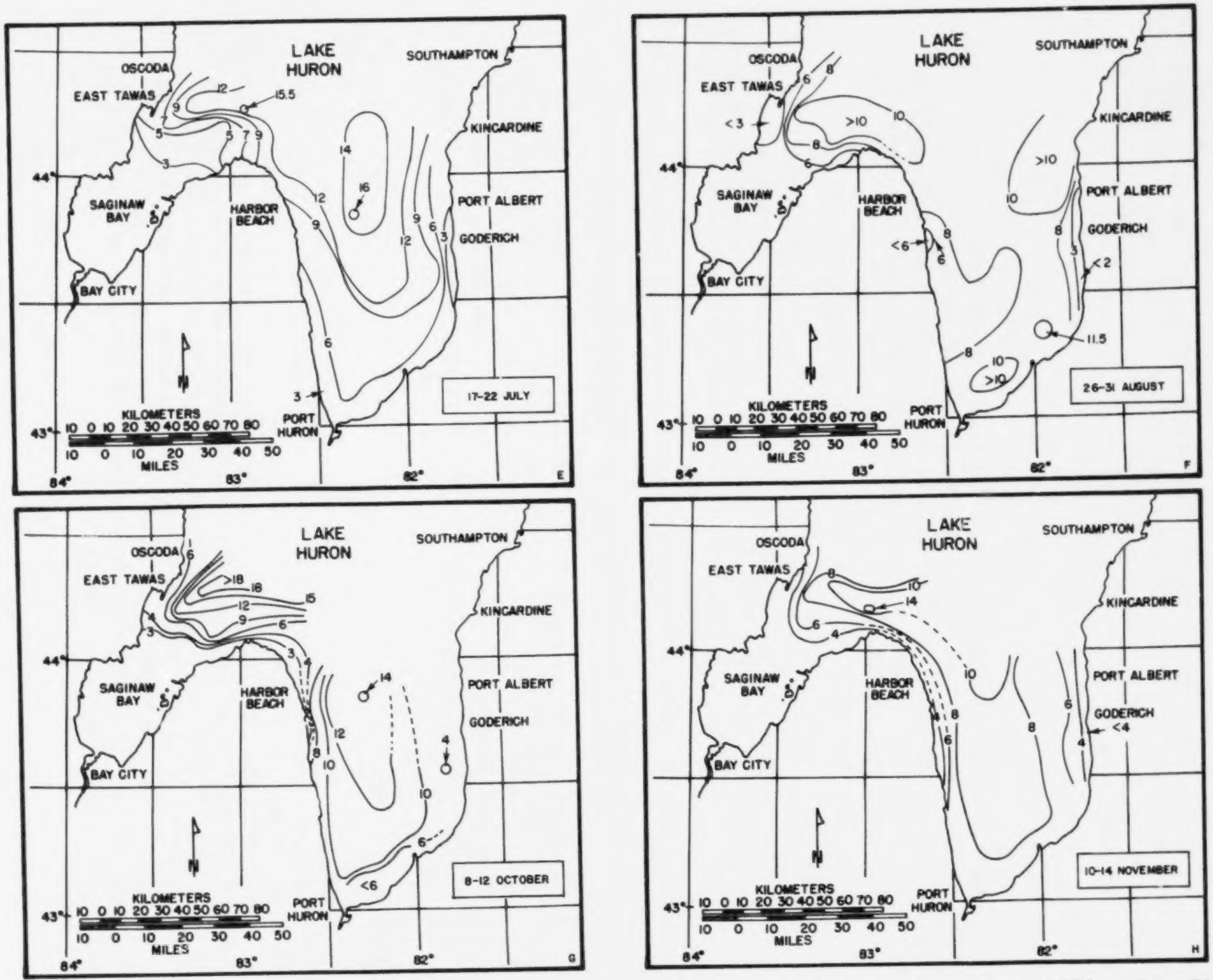

LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
KILOMETERS
MILES
44°
43°
84°
83°
82°
28 APRIL – 3 MAY
14–17 MAY
4–8 JUNE
17–21 JUNE
A
B
C
D
<5
7.8
7.5
0.3
<2
>6
2.5
<1
>7

Figure 3.10. Secchi disc transparency (m) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates. (continued).


LAKE HURON
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SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
44°
43°
84°
83°
82°
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
MILES
17-22 JULY
E
15.5
16
26-31 AUGUST
F
11.5
>10
<3
<6
<2
8-12 OCTOBER
G
>18
<6
10-14 NOVEMBER
H
<4

Figure 3.10 (continued). Secchi disc transparency (m) in southern Lake Huron, 1974. See Figure 3.4 for cruise dates.

Autumnal Cooling

A very sharp gradient in Secchi disc transparency was found during the October cruise at the mouth of Saginaw Bay where transparencies ranged from 3 to >18 m (the maximum transparency during this study) over a distance of about 30 km (Figure 3.10g). Some of the low transparency water was being transported to the east and south and was present along the western shore near Harbor Beach. This pattern of transparencies at the mouth of Saginaw Bay persisted on the November cruise (Figure 3.10h) although the gradients were not as sharp.

SEASONAL CHANGES

Averages of selected variables for Saginaw Bay and open Lake Huron were plotted to show seasonal variation. In general, there was a distinct difference between the stations in Saginaw Bay and those in the open lake; however, the differences between stations in the northern and southern parts of our study area were small.

Temperature

A distinct seasonal cycle in the surface water temperature was obvious for the three areas. The expected relationship of water temperature to depth of the water column was observed; water temperature in Saginaw Bay was warmer during the warming period and cooler during the cooling period than in the deeper waters of the open lake (Figure 3.11). Maximum temperatures for the three groups of stations exceeded 20°C during cruise 6 at the end of August, and temperatures may have been greater in September when no samples were obtained.

Sampling did not begin early enough in the spring to obtain data during the entire warming period, especially in Saginaw Bay, and did not continue long enough in the autumn for water to cool to the temperature of maximum density. On the last cruise (November 10-14), water temperatures averaged 9 to 10°C.

Chloride

Average concentrations of chloride were larger at the Saginaw Bay stations than at stations in the open part of the lake (Figure 3.12). In addition, chloride concentrations in the bay were greater on cruises 3, 4, and 5 (early June to mid-July) than at other times of the year. Whether this increase in concentration in outer Saginaw Bay resulted from a buildup of chloride in the bay during the winter and spring is not known. Data for water temperature and chemistry indicate that exchange between Saginaw Bay and the open part of the lake is limited during the thermal bar period. Another explanation for large concentrations in the spring is that this is the period of maximum loading from runoff.

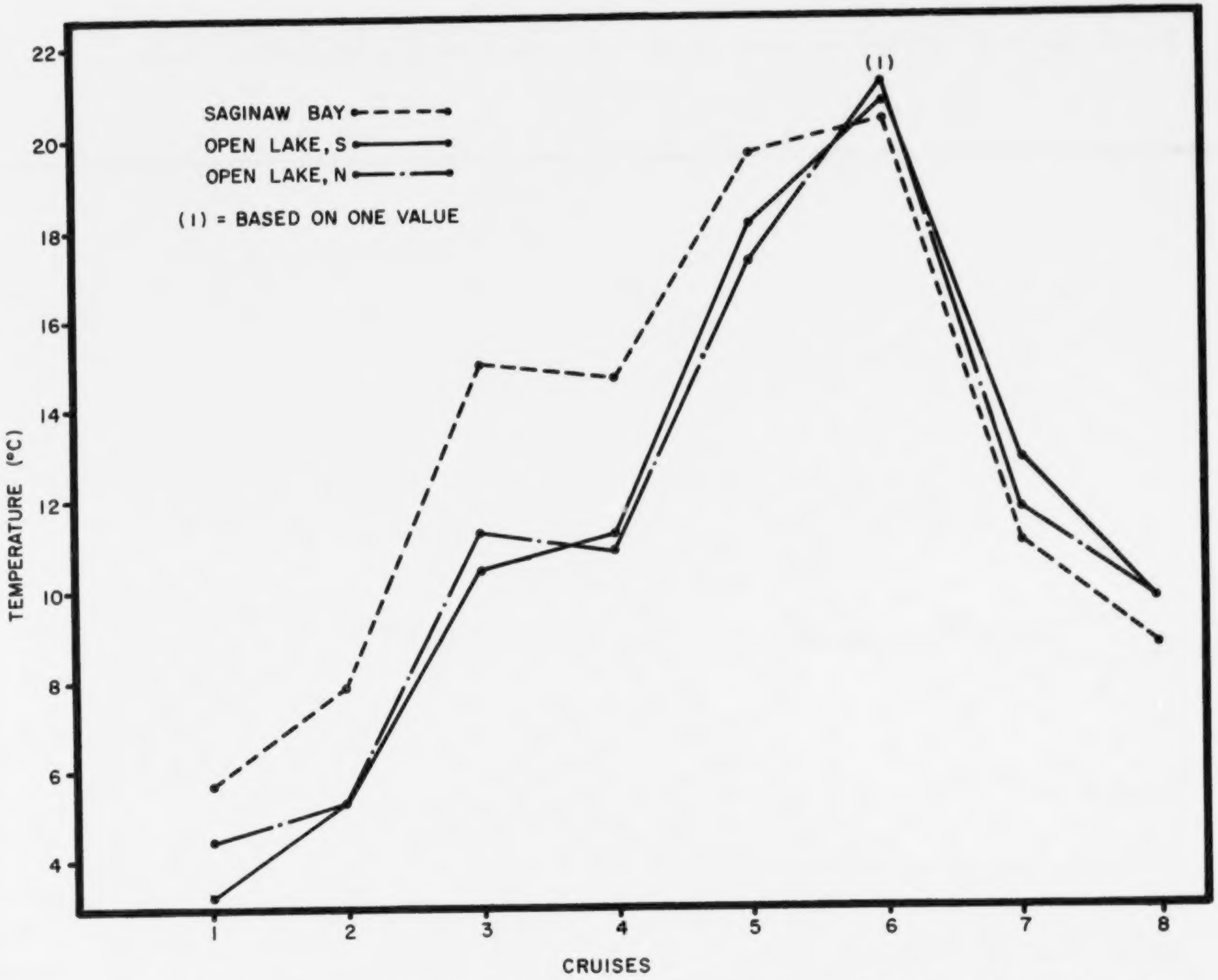


Figure 3.11. Seasonal changes in surface water temperature (^{o}C) for selected stations in southern Lake Huron, 1974. Data plotted are averages for Stations 36-40 in Saginaw Bay, Stations 10, 11, 13, and 66 in the open lake (South) and Stations 54, 55, 56, and 58 in the open lake (North).

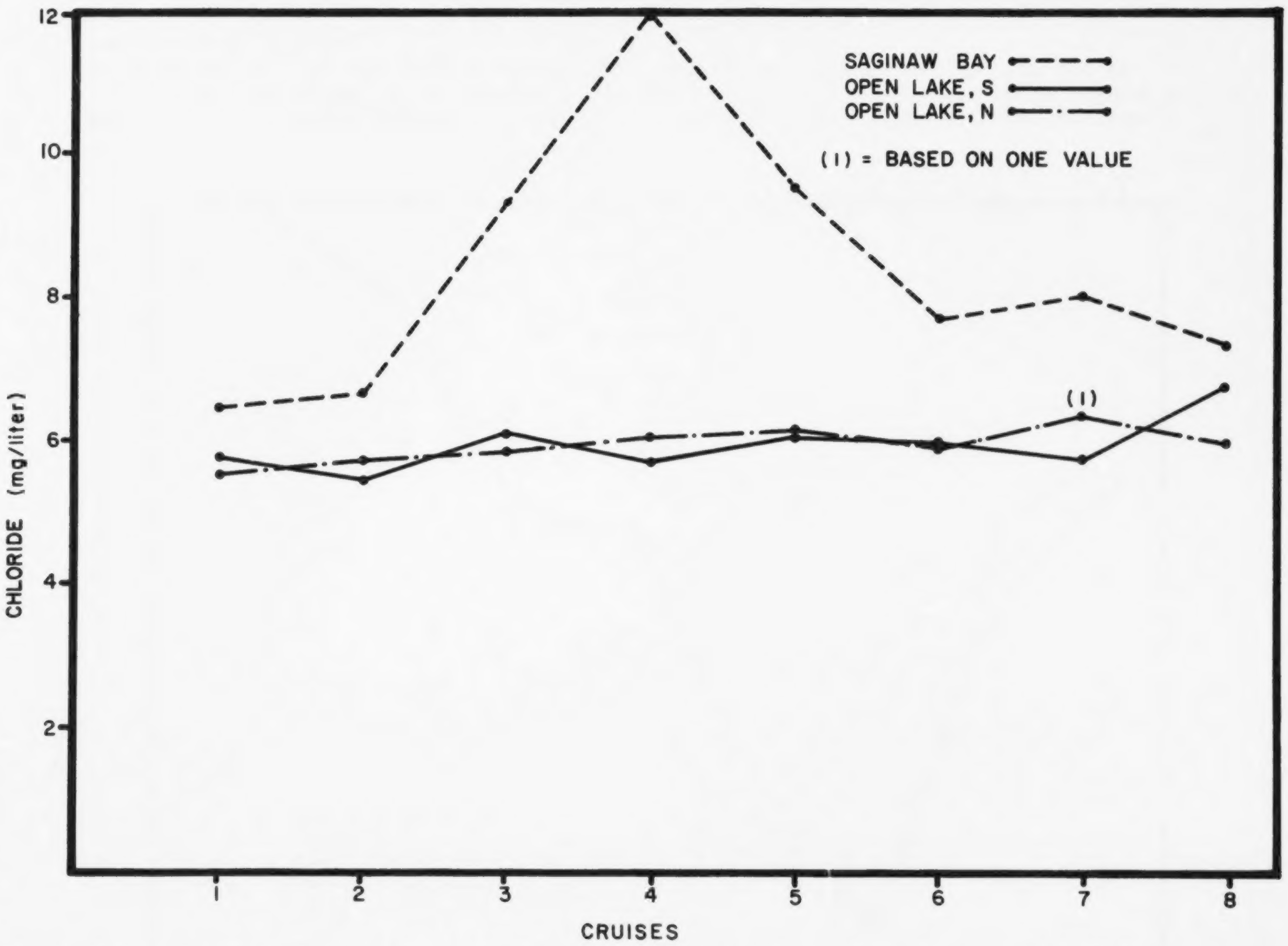


Figure 3.12. Seasonal changes in surface concentrations of chloride (mg/1). For additional information about data plotted, see Figure 3.11.

Dissolved Reactive Silica

A seasonal cycle in dissolved reactive silica is apparent both for Saginaw Bay and open Lake Huron (Figure 3.13). The two regions differ in that the rate of decrease in Saginaw Bay is much greater than that in the open lake and in that the minimum concentration in Lake Huron is larger than the minimum concentration in Saginaw Bay.

The decrease in concentration of silica in Saginaw Bay during the spring amounted to 0.9 mg/l and occurred over a period of about 40 days from the end of April to early June. The average rate of this decrease was 0.022 mg/l/day. In the open lake, the silica concentration decreased a comparable amount, but the time required to reach the minimum found in October was about 160 days. The average rate of decrease in the open lake was, therefore, only 0.0057 mg/l/day.

On the first analysis, the rates of silica decrease in outer Saginaw Bay and open southern Lake Huron appear to be very different. Different physical processes in the two environments, however, would tend to reduce these differences if calculations were considered on an areal basis instead of a volumetric basis. In the 40 days in which silica decreased in Saginaw Bay, the volume of the epilimnion would have changed little compared to the volume of the epilimnion in the open lake. In fact, the open lake was not stratified until early June (Figure 3.4c) when silica concentrations in Saginaw Bay were the lowest observed during our study. Therefore, until early June, diatoms in the open lake undoubtedly were utilizing silica and decreasing concentrations throughout the water column. In addition, after the lake stratified, the epilimnion in the open lake would have increased proportionately much more than that in Saginaw Bay.

Nitrate Nitrogen

The seasonal cycle in concentration of nitrate nitrogen was not as pronounced as it was for silica. In the open lake, concentrations decreased gradually during the entire period of sampling (Figure 3.14). The expected autumn increase in concentration resulting from entrainment of nitrate rich hypolimnetic water was not observed. In outer Saginaw Bay, data did not fit the expected seasonal pattern because the largest concentrations occurred on cruise 4 during mid-June.

Part of the explanation for the lack of a seasonal cycle in outer Saginaw Bay is the lack of nitrate data for the August cruise when the lowest nitrate nitrogen concentrations would have been expected. The absence of the expected seasonal pattern was in part the combination of two factors. First, Saginaw Bay warmed much faster than the open lake, so one would not necessarily expect the seasonal pattern to be the same for the two environments. Second, the largest nitrate concentrations were found on cruise 4 when maximum chloride concentrations also were observed (Figure 3.12), indicating that the proportion of inner Saginaw Bay water was greatest for this cruise during June. Smith et al. (1977) have shown that concentrations of nitrate nitrogen were greater in inner Saginaw Bay than in the outer bay during this period in 1974.

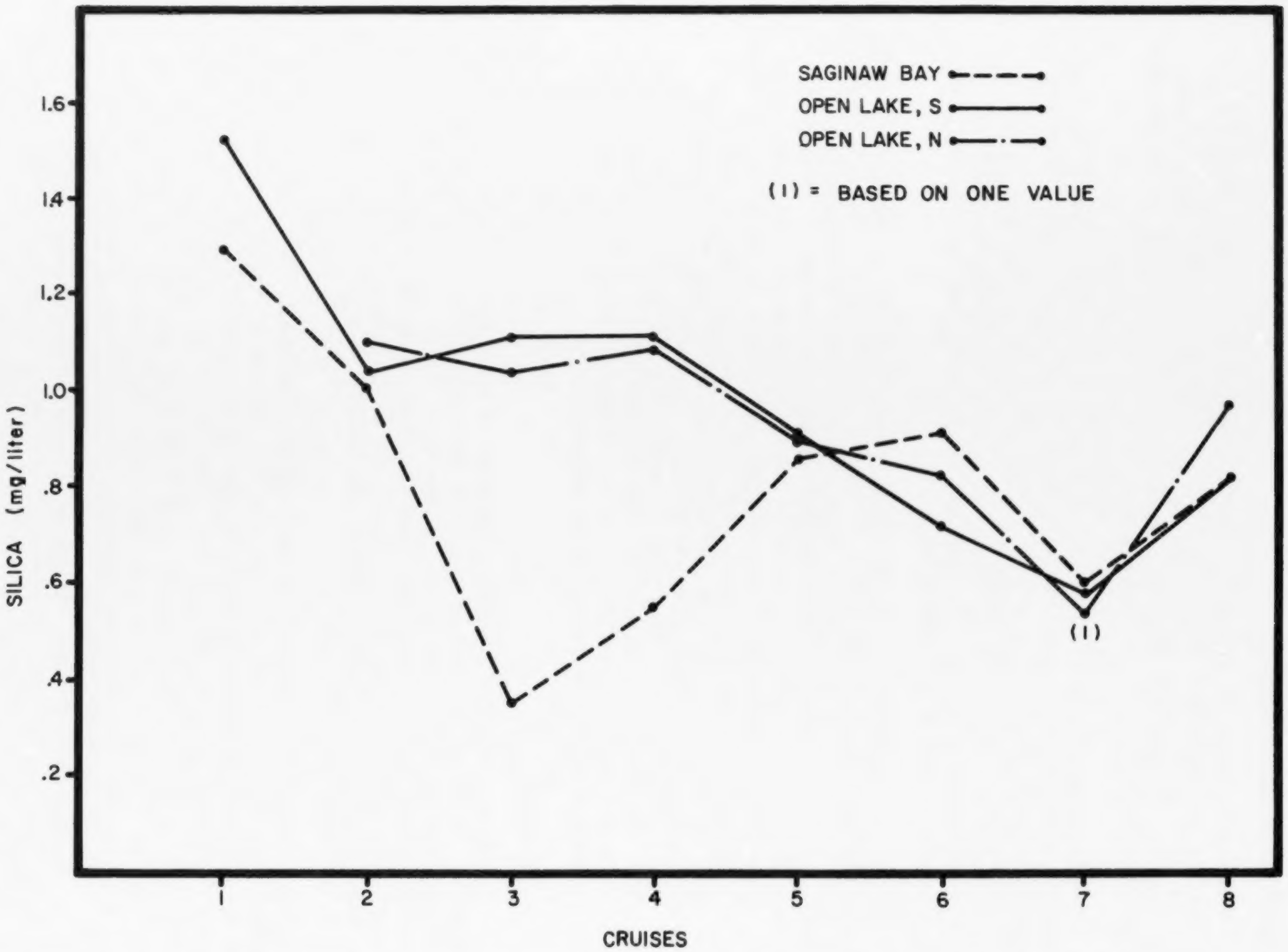


Figure 3.13. Seasonal changes in surface concentrations of silica (mg/l). For additional information about data plotted, see Figure 3.11.

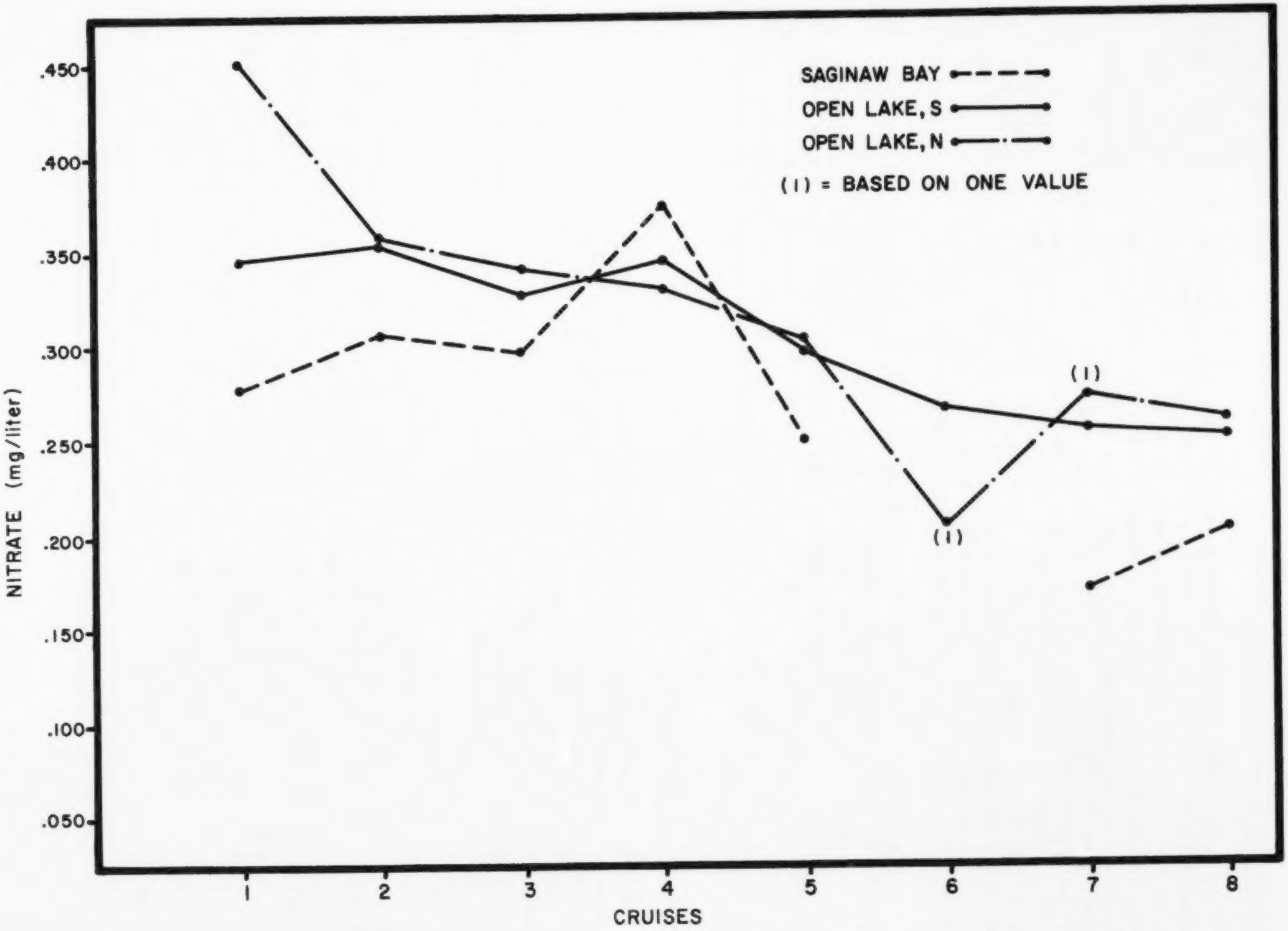


Figure 3.14. Seasonal changes in surface concentrations of nitrate nitrogen (mg/1). For additional information about data plotted, see Figure 3.11.

Chlorophyll a

In both outer Saginaw Bay and in the open lake, maximum chlorophyll *a* concentrations were found in mid-May during cruise 2 (Fig. 3.15). After cruise 2, concentrations decreased generally until cruise 7 in October when there was an obvious increase in concentration in Saginaw Bay and an indication of an increase at the open lake stations. Detecting seasonal differences in absolute concentrations for the open lake stations is obviously more difficult than in Saginaw Bay because the summer concentrations in the open lake were <1.0 μg/l. Although small, minimum concentrations in outer Saginaw Bay were <1.5 μg/l or several times larger than those at the open lake stations. Data for the one station sampled in outer Saginaw Bay in mid-June indicate elevated chlorophyll *a* levels, possibly the result of intrusion of inner Saginaw Bay water.

It is also obvious that the standing crop of chlorophyll *a* in outer Saginaw Bay was greater than that found at the open lake stations (Figure 3.15). Average concentrations for the stations in Saginaw Bay ranged from 1.5 to 5.0 μg/l, a range in concentrations that overlapped with those in the open lake only for cruises 1 and 2. In the open lake, average concentrations ranged from 0.3 to 3.8 μg/l, but if the first two cruises or the spring maximum values are excluded, the average concentrations ranged only from 0.3 to 1.5 μg/l.

Secchi Disc Transparency

Secchi disc transparency varied seasonally at the open lake stations, but the variation was not strictly the inverse of that observed for chlorophyll *a* concentrations. If the one large value for the north lake stations is excluded, transparency values generally were greatest when chlorophyll concentrations were least and were smallest when the chlorophyll concentrations were greatest (Figure 3.16). A similar relationship between transparency and chlorophyll *a* concentrations also was found at the Saginaw Bay stations.

Transparency, as measured with the Secchi disc in our studies, was compared with data collected in 1954 by Ayers et al. (1956). Data in 1954 were collected in June, July, and August. Compared with our data collected in 1974, transparencies in 1954 were generally greater. The largest differences between the 2 years occurred when the June data were compared; in 1954, tranparencies greater than 8 m occurred over a large part of southern Lake Huron whereas during 1974, transparencies were generally 7 m or less in the same areas. The biggest difference was in maximum values that were 13 m in 1954 and only 7 m in 1974. In addition, the area in which transparency was >12 m in 1954 only had a transparency of >6 m in 1974. In July 1974, a large area had transparencies >12 m with the value at one station being 16 m, but in 1954 the transparency was >14 m over a large area with a maximum value of 19 m. In August 1974, transparencies in the open lake south of Saginaw Bay ranged from 8 to 10 m, but in 1954, values as large as 11 m were observed.

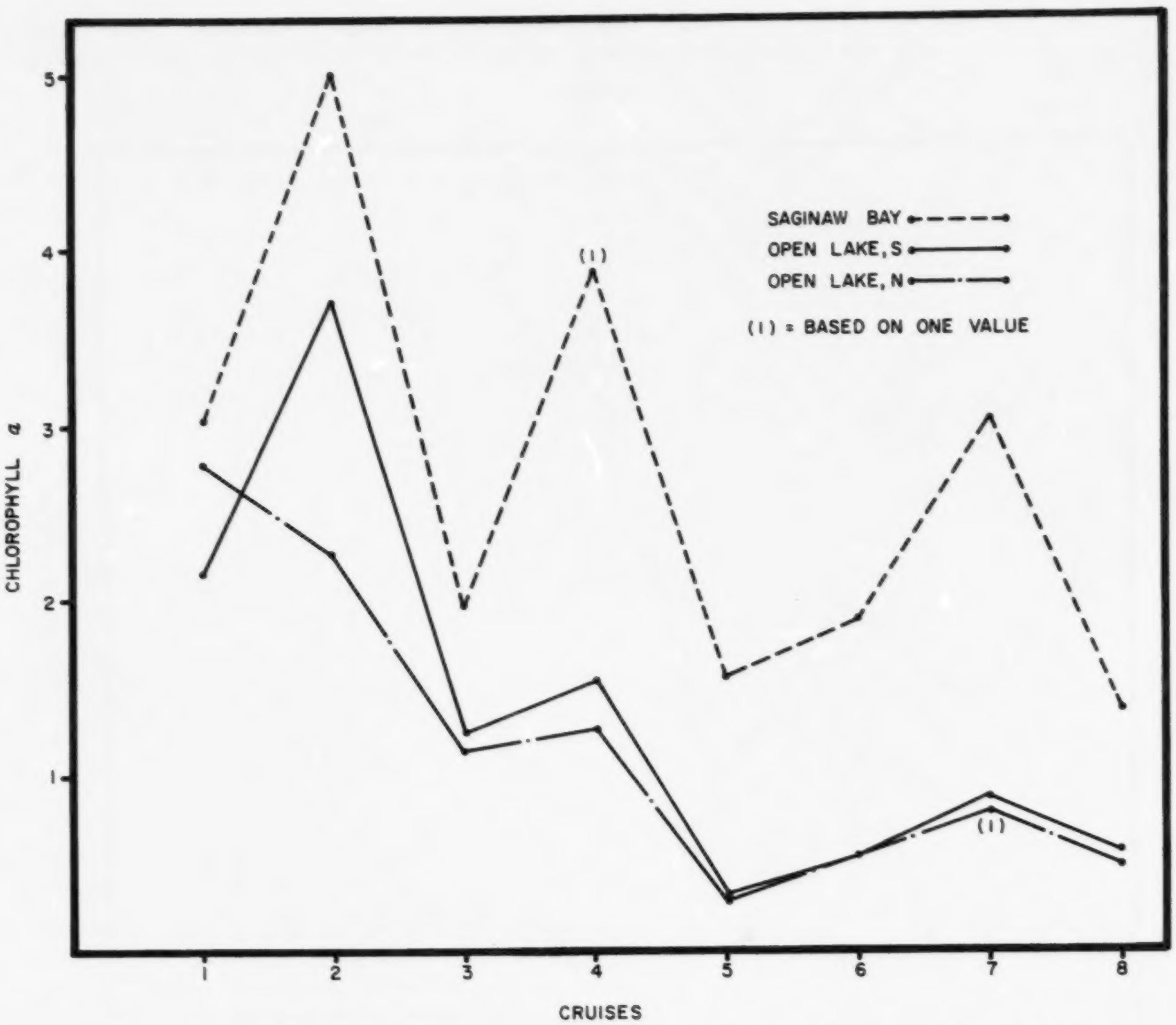


Figure 3.15. Seasonal changes in surface concentrations of chlorophyll a (µg/l). For additional information about data plotted, see Figure 3.11.

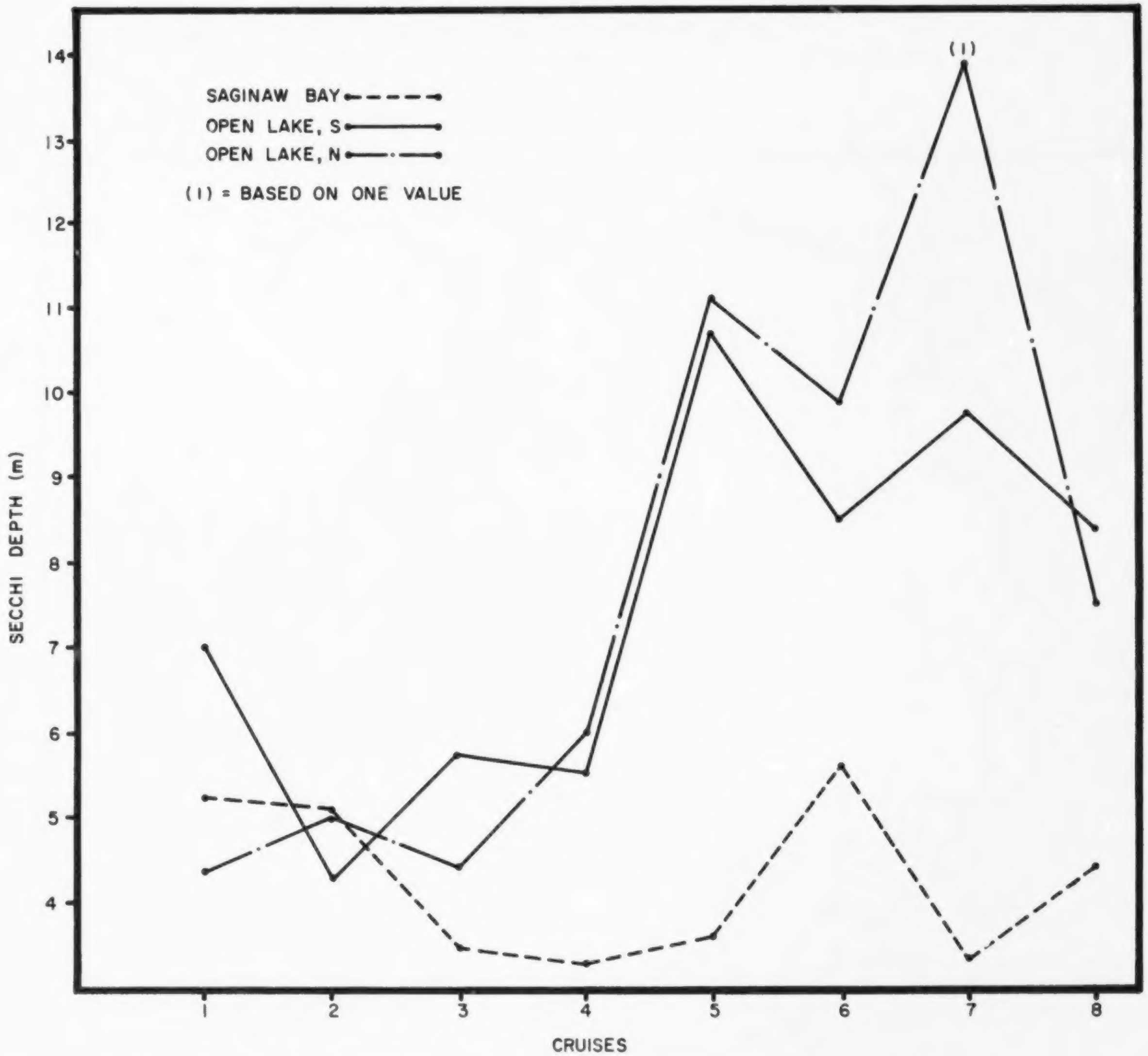


Figure 3.16. Seasonal changes in Secchi disc transparency (m). For additional information about data plotted, see Figure 11.

TRANSPORT FROM SAGINAW BAY

One of the objectives of our study was to assess the importance of transport of materials from Saginaw Bay to Lake Huron. This objective was accomplished by studying the distribution of water masses in the vicinity of the mouth of Saginaw Bay. Although we did not study currents directly during our cruises, it is obvious that the distribution of water masses is the direct result of water movement. During 1974, at the same time our data were collected, Danek and Saylor (1975) studied the currents in Saginaw Bay and reviewed results of previous studies of the currents of Saginaw Bay and Lake Huron, including those by Ayers et al. (1956), Johnson (1958), and Beeton et al. (1967).

Previous conclusions from studies of currents in Saginaw Bay generally have been that current patterns are complex and are highly dependent on local winds. Some of the complexity in current patterns at the mouth of Saginaw Bay may be caused by rapid response to winds because one would not expect an effect on circulation patterns in the main part of the lake to be as rapid. The typical pattern of transport from Saginaw Bay around the thumb and then southward has been observed many times; but other patterns of currents are also quite common, leading to the general conclusion that current patterns are complex in and near the mouth of Saginaw Bay.

Influences of the wind on surface currents and water transport would have been relatively less during the thermal bar cruises than on subsequent cruises. During the thermal bar period, surface water temperatures vary horizontally, and in addition, during periods of warm weather, a thermal atmospheric inversion frequently occurs near the water's surface. As a result, the effective wind energy at the water's surface varies greatly depending on the difference between the air and water temperatures; therefore, wind velocities on land may be much greater than those near the lake surface. The distribution of temperature (Figures 3.4a and b), chloride (Figures 3.5a and b), and other variables during the first two cruises indicates little or no surface transport of water from Saginaw Bay.

On 2 of the 3 days preceding the third cruise, winds were moderate from the south to southeast, averaging about 2 knots at the Selfridge station (Appendix A) and were stronger about 4 knots at the Wurtsmith station (Appendix B). On the second and third days before the cruise, the wind velocity at Wurtsmith averaged only 4 knots from the ESE. During the cruise, winds averaged from 6-11 knots from the SSE to SSW. Water transport from Saginaw Bay apparently occurred along the north shore as indicated by the intrusion of a water mass with Saginaw Bay water characteristics, high chloride (Figure 3.5c) and low silica (Figure 3.7c), toward the main lake. This pattern of water masses conforms with the current pattern proposed by Danek and Saylor (1975) for southwest winds.

The fourth cruise was preceded by SSW winds of 6 knots or less. During the cruise, velocities ranged from 3 to 6 knots at Selfridge (Appendix A) and from 6 to 9 knots at Wurtsmith (Appendix B). These winds were generally S to SW, shifting to N at Wurtsmith on the last day of the cruise. On cruise 4, there was some indication of intrusion of Saginaw Bay water along the northern shore near East Tawas, but the most pronounced feature was the presence of Saginaw Bay water along the southern shore extending around the thumb toward Harbor Beach. Isopleths for temperature (Figure 3.4d), chloride (Figure 3.5d), silica (Figure 3.7d), and chlorophyll a (Figure 3.9d) indicate extensive transport from Saginaw Bay. The best indicator of this transport is the presence of the 15-mg/l isopleth for chloride across the mouth of Saginaw Bay (Figure 3.5d).

Northerly winds, averaging as large as 8-9 knots, preceded the fifth cruise. During the 6 days of the cruise, winds were quite variable in velocity and direction. On July 17, the first day of the cruise, winds shifted to the south at Selfridge and averaged about 5 knots. On the second day, the direction shifted to WSW, and the velocity increased, averaging 9 to 10.5 knots. On the next two days, the wind shifted to W and N, but average wind velocity decreased to 6 to 8 knots. Wind velocities decreased on the last 2 days, and the direction shifted to N to NNE. Velocities were 1.5 and 2.7 knots at Wurtsmith (Appendix B), but were much greater at Selfridge (Appendix A) averaging 3.5 and 5.0 knots. Current patterns expected from the variable wind conditions would be complex. The distribution of water masses shows a slight intrusion of Saginaw Bay water near the thumb toward the northeast to the open lake (Figures 3.5e, 3.6e, and 3.8e) rather than around the thumb. In addition, there is evidence for a slight intrusion of open lake water into Saginaw Bay near the northern shore (Figures 3.5e-3.8e). The transport is obviously weak but is the type expected from current patterns shown by Danek and Saylor (1975) for northeast winds that occurred during part of the cruise.

Prior to the sixth cruise, winds were northerly and moderate with velocities averaging 4 knots. On the day before the cruise started, winds shifted to the east. On the first day of the cruise, winds were moderate, averaging about 6 knots from the SW. During the next 3 days, the velocity decreased, generally averaging <4 knots, and the direction was variable ranging from the west to the northeast. Winds then shifted to the south at <4 knots and to the west on the last day of the cruise when the velocity increased to 7 to 8 knots. With these variable wind conditions, current patterns are probably not predictable. There was an intrusion of water with elevated chloride (Figure 3.5f) and high chlorophyll a (Figure 3.9f) from Saginaw Bay along the northern shore near East Tawas toward the open lake. The distribution of isopleths, however, does not suggest transport of water out of the bay.

The seventh cruise was preceded by several days of winds, from 7 to 11 knots from the SW shifting to NW on the day before the cruise started. During the first 4 days of the cruise, wind velocity averaged from 3 to 5 knots, and the direction varied from S to W. On the last day of the cruise, the direction shifted to NW, and the velocity increased to 6 to 7 knots. On cruise 7, there appears to have been an intrusion of open Lake Huron water in the middle portion of Saginaw Bay and strong transport of Saginaw Bay water to the northeast along the southern shore around the thumb area toward Harbor Beach (Figures 3.5g, 3.8g, and 3.9g) Isopleths for chloride (Figure 3.5g) and chlorophyll a (Figure 3.9g) also indicate a lesser but pronounced transport of water along the northern shore from Saginaw Bay. The intrusion of water in the middle part of the bay indicates a different current pattern than that suggested by Danek and Saylor (1975) for southwest winds.

Prior to the last cruise, winds were W to SW and were moderate, being 2 to 3 knots. On the first day of the cruise, winds shifted to the south and increased in velocity to 7 to 10 knots on the second day of sampling. During the last 3 days, wind direction ranged from southwest to west, and velocity increased to 9 to 12 knots on the last day. The distribution of water masses was similar to that for cruise 7 in that there was an intrusion of open lake water in the mid portion of Saginaw Bay and also evidence for transport along the south shore around the thumb with weaker transport to the open lake along the north shore.

DISCUSSION

It has been recognized in many investigations that there is a great amount of variability in most environmental parameters within the Lake Huron system, especially if values from Saginaw Bay are compared with any other area in the lake (Beeton et al., 1967; Schelske and Roth, 1973). Saginaw Bay is different than other parts of Lake Huron because the Saginaw River carries large loads of many materials, increasing concentrations in inner Saginaw Bay in comparison to those found in the open parts of the lake. As shown by Smith et al. (1977), the Saginaw River in 1974 carried loads of chloride, total phosphorus, and total nitrate nitrogen that were large enough to increase concentrations in lower Saginaw Bay in comparison to those found either in outer Saginaw Bay or in the open lake. Concentrations of the conservative ions, sodium, calcium, and magnesium, were also greater in Saginaw Bay than in the open lake.

The large nutrient loads from the Saginaw River produced favorable conditions for large phytoplankton standing crops in Saginaw Bay. Average yearly chlorophyll _a_ concentrations in lower Saginaw Bay were 30 μg/l with maximum concentrations during the summer ranging to more than 70 μg/l. Smith et al. (1977) also reported concentrations of total phosphorus in lower Saginaw Bay that averaged more than 35 μg/l.

In contrast to the relatively highly polluted waters in Saginaw Bay are the other major sources of surface water inputs to the main body of Lake Huron. Waters from Lake Superior, the North Channel, and Georgian Bay have very high quality compared to Saginaw Bay or to any other area or part of the Great Lakes. The other important source of surface water to Lake Huron is the outflow from Lake Michigan, which also is high quality water but has larger concentrations of total phosphorus than either Lake Superior or Lake Huron and differs chemically from these waters in several other respects (Schelske et al., 1976).

The Upper Great Lakes Reference Group segmented the main part of Lake Huron, the North Channel, and Georgian Bay into nine areas to reflect variability in environmental parameters. Nearshore zones, areas <3 km from shore or with depths <15 m, were excluded in the segmentation as was Saginaw

Bay (International Joint Commission, 1977). It is surprising to note how little average values for nutrients differed among the segments in 1974 (Figure 3.17). For example, average total phosphorus concentrations among the segments, excluding those for the North Channel, ranged only from 4.8 to 5.7 μg/l. The lowest average concentration of total phosphorus was 4.8 μg/l in Segment 6. Without this value, average concentrations for 7 to 15 cruises among the remaining segments ranged from 5.3 to 5.7 μg/l.

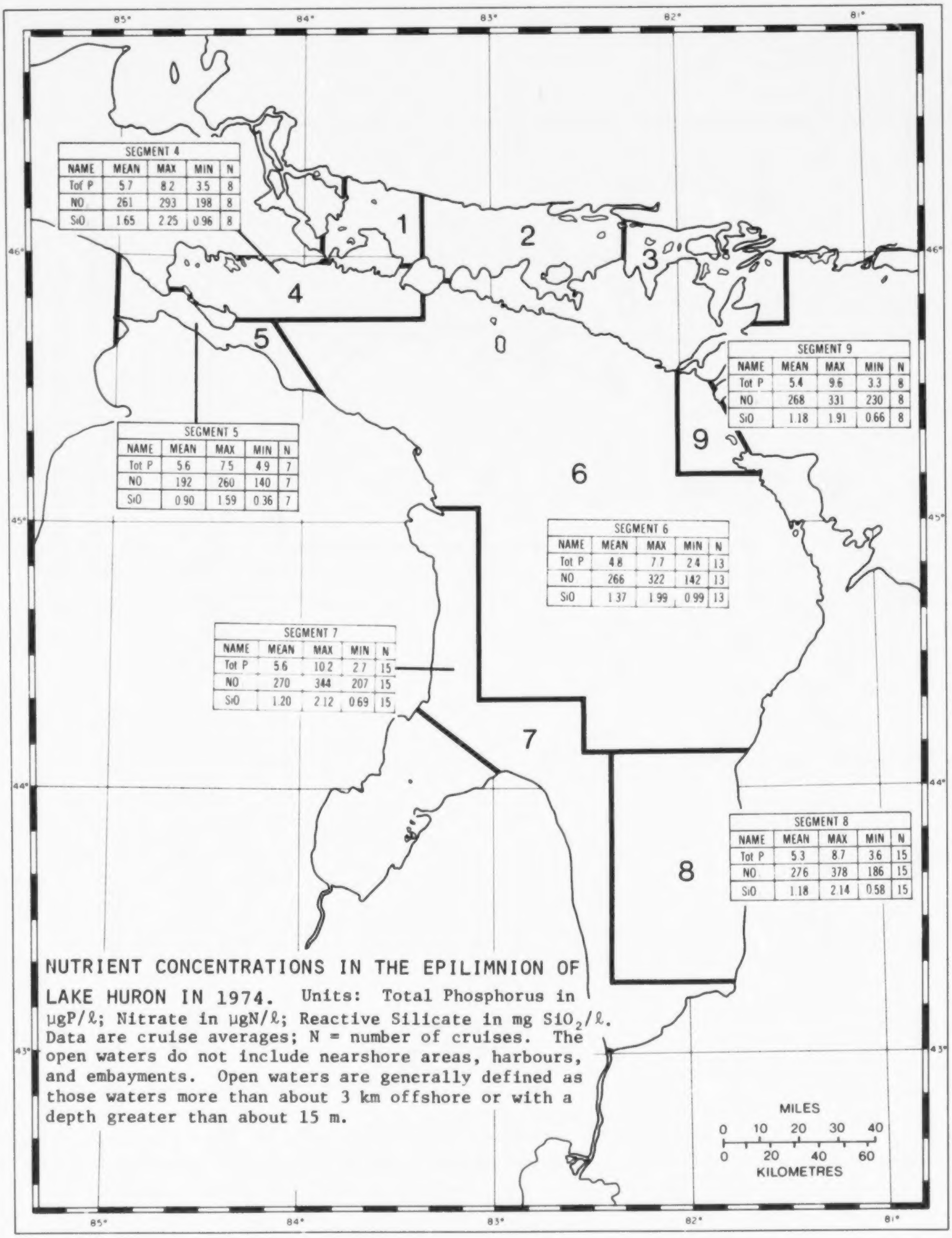
Differences among the segments in the average concentrations of silica and nitrate were larger than those for average total phosphorus concentrations (Figure 3.17). If the maximum and minimum concentrations as well as the average concentrations are compared for different segments, it is possible to distinguish differences among the segments. The range in concentrations of silica and nitrate nitrogen is mainly attributable to seasonal changes, as shown in Figures 3.13 and 3.14.

The report by the International Joint Commission (1977) utilized Segment 6 to establish average conditions for the lake. Data we collected for this report do not reflect conditions in Segment 6 because most of our stations were in Segments 7 and 8 and in Saginaw Bay (Figure 3.18). The average values for open lake stations in Figures 3.11-3.16 represent conditions in Segment 8. No attempt was made to plot seasonal averages for the data collected in Segment 7 because of cruise-to-cruise variability in data at each station. Conditions at our stations in Segment 7 were influenced most by current patterns and water transport from Saginaw Bay; therefore, water quality at any given time is greatly influenced by the proportion of Saginaw Bay water at any given station. This type of variability is obvious for the data from Stations 36-40, which were averaged to reflect variable conditions in outer Saginaw Bay.

Horizontal variations in physical, chemical, and biological variables in our study area were strongly influenced by the presence of readily identifiable water masses. These water masses with distinct characteristics were either transported from Saginaw Bay to the open lake or from the open lake into Saginaw Bay. One general pattern that was observed on several cruises was the movement of water out of Saginaw Bay near one shoreline and the compensating transport of water into Saginaw Bay along the opposite shoreline. Differing patterns of transport are undoubtedly dependent on meteorological conditions, particularly wind direction and velocity for the several hours to several days prior to the time data were collected.

As one aid in interpreting patterns of water masses, we compiled meteorological information from two shore locations near our study area. At both locations, Selfridge Air Force Base and Wurtsmith Air Force Base, wind speed and direction were recorded hourly during 1974. This set of data has been reduced to daily averages that are presented in Appendices A and B. Presenting data in this manner may introduce some bias, but it does identify storm periods that have greater than average wind velocities and that affect water currents more than periods with smaller inputs of wind energy.

The transport of Saginaw Bay water to the open lake was only apparent from the distribution of water masses on two or three of our eight cruises.



SEGMENT 4				
NAME	MEAN	MAX	MIN	N
Tot P	5.7	8.2	3.5	8
NO	261	293	198	8
SiO	1.65	2.25	0.96	8

SEGMENT 9				
NAME	MEAN	MAX	MIN	N
Tot P	5.4	9.6	3.3	8
NO	268	331	230	8
SiO	1.18	1.91	0.66	8

SEGMENT 5				
NAME	MEAN	MAX	MIN	N
Tot P	5.6	7.5	4.9	7
NO	192	260	140	7
SiO	0.90	1.59	0.36	7

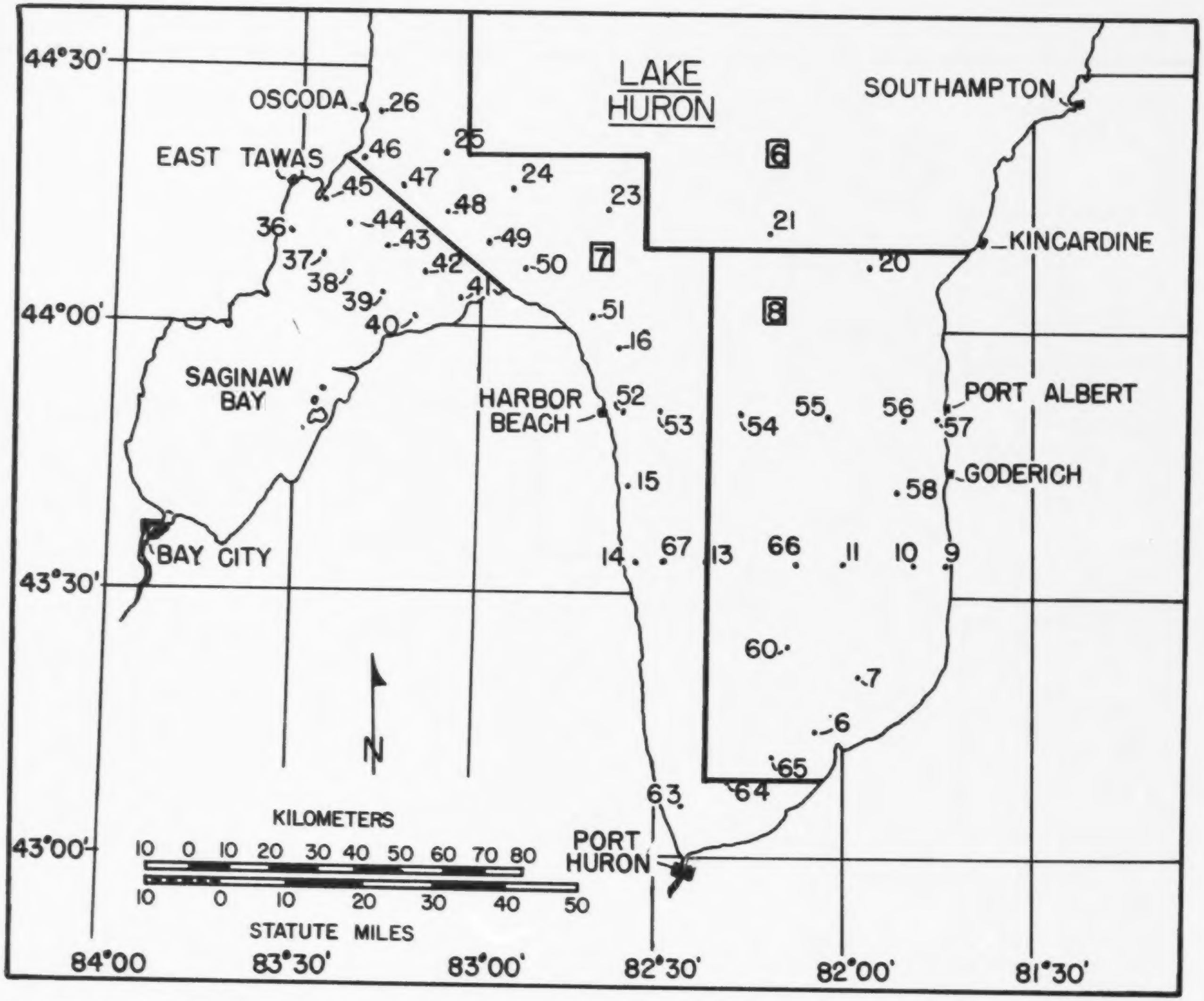
SEGMENT 6				
NAME	MEAN	MAX	MIN	N
Tot P	4.8	7.7	2.4	13
NO	266	322	142	13
SiO	1.37	1.99	0.99	13

SEGMENT 7				
NAME	MEAN	MAX	MIN	N
Tot P	5.6	10.2	2.7	15
NO	270	344	207	15
SiO	1.20	2.12	0.69	15

SEGMENT 8				
NAME	MEAN	MAX	MIN	N
Tot P	5.3	8.7	3.6	15
NO	276	378	186	15
SiO	1.18	2.14	0.58	15

NUTRIENT CONCENTRATIONS IN THE EPILIMNION OF LAKE HURON IN 1974. Units: Total Phosphorus in μgP/ℓ; Nitrate in μgN/ℓ; Reactive Silicate in mg SiO_2/ℓ. Data are cruise averages; N = number of cruises. The open waters do not include nearshore areas, harbours, and embayments. Open waters are generally defined as those waters more than about 3 km offshore or with a depth greater than about 15 m.

Figure 3.17. Nutrient concentrations in the epilimnion of Lake Huron in 1974. (International Joint Commission, 1977)


LAKE HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
6
7
8
26
25
24
23
21
20
46
47
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49
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42
41
36
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38
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57
58
15
14
67
13
66
11
10
9
60
7
6
65
64
63
N
KILOMETERS
10 0 10 20 30 40 50 60 70 80
10 0 10 20 30 40 50
STATUTE MILES
44°30'
44°00'
43°30'
43°00'
84°00
83°30'
83°00'
82°30'
82°00'
81°30'

Figure 3.18. Map of southern Lake Huron showing relationship between 1974 stations sampled by Great Lakes Research Division and segmentation used by the International Joint Commission.

The most obvious transport was the previously reported typical pattern of transport out of the bay along the southern shore around the thumb, then southward toward Harbor Beach. Lakeward transport was also evident, although to a lesser extent, along the northern shore near East Tawas. Current patterns reported by Sloss and Saylor (1975) for 15-day periods show that currents flow outward to the lake from the bay along both the southern and the northern shores, so the presence of Saginaw Bay water moving out of the bay along the northern shore is not unexpected. Currents have been reported to be complex and strongly influenced by short-term meteorological events at the mouth of and in Saginaw Bay, so one would expect that water transport would also be complex.

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SECTION 4

STATISTICAL INFERENCES FROM SOUTHERN LAKE HURON -- 1974

by Russell A. Moll

Water quality in southern Lake Huron during 1974 was characterized by large contrasts. Conditions vary from nearly pristine waters in the center of the lake to highly eutrophic waters in Saginaw Bay and along the Ontario shoreline. Because of the large, complex database compiled for southern Lake Huron, multivariate statistics were employed to aid in the interpretation of the data. The purpose of this chapter is to present the results of several statistical analyses and the ecological interpretation that follows those analyses.

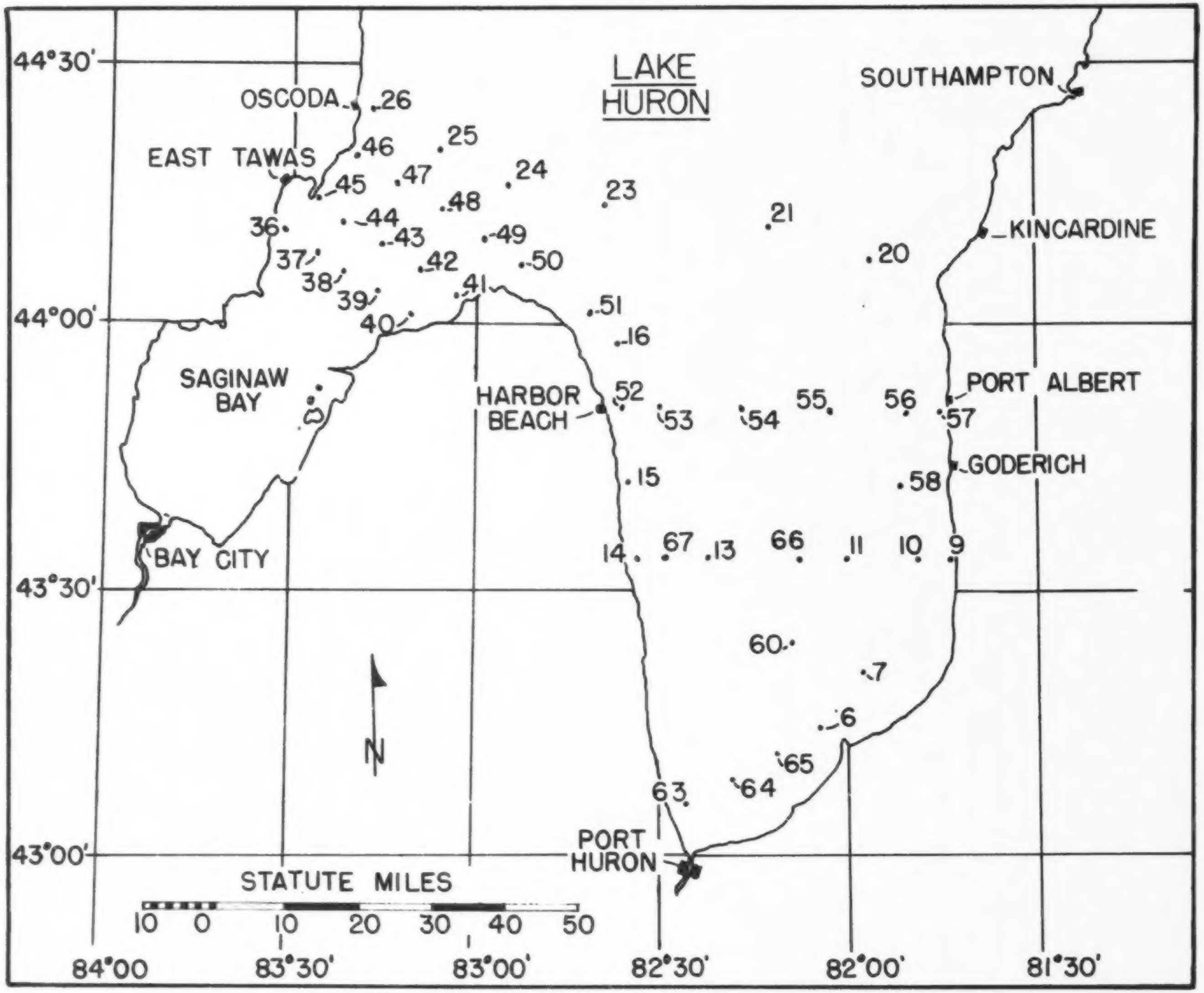
The approach used in the analyses was not without precedent in that we successfully analyzed data collected in 1973 from the Straits of Mackinac (Moll et al., 1976). But, the Lake Huron data differed from the Straits data in that eight cruises were conducted as compared to three, a larger area was sampled, a larger portion of the year was sampled (April to November), and more variables were measured. Because of the larger spatial and temporal range of the Lake Huron data, different techniques were necessary than were used in the Straits of Mackinac data.

METHODS

Forty-four stations (Figure 4.1) were sampled for fifteen variables on eight cruises. Although all stations were not visited on every cruise, the data set was relatively complete. Missing stations were primarily the result of poor weather during sampling, while missing variables were the result of failure of a technique where immediate sample analysis was necessary, although both were not particularly common.

The sampling grid covered Lake Huron from Oscoda to the southern end of the lake near Port Huron (Fig. 4.1). Stations were concentrated in the mouth of Saginaw Bay, as this area is known for highly contrasting water quality. Samples were not collected farther in the bay than Charity Island, since our intent was to reveal the influence of bay water on the open lake.

The fifteen variables measured included chemical, physical, and biological variables with a bias toward explaining the function of phytoplankton in the lake. Many of the samples were analyzed on board the research vessel; however, some samples were brought to our Ann Arbor


LAKE HURON
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
26
25
46
24
47
45
48
23
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64
63
N
STATUTE MILES
10
0
10
20
30
40
50
44°30'
44°00'
43°30'
43°00'
84°00
83°30'
83°00'
82°30'
82°00'
81°30'

Figure 4.1. Location of SLH sampling stations.

laboratories when shipboard processing was not feasible. A more complete description of the sampling techniques is found in Section 3.

Statistical Methods

After simple statistics were calculated for each variable, the data were prepared for multivariate analysis by standardization. This meant that each variable had a mean set equal to 0.0 and a standard deviation set equal to 1.00 (Sokal and Rohlf, 1969). This transformation had the effect of putting all variables in the same numerical range or intercomparison. No other transformations were performed, as the multivariate analyses used were not particularly sensitive to non-normality (Van de Geer, 1971). Correlations (simple product-moment) were calculated between all standardized variables; all possible pairs of measurements were used to find the correlation between two variables rather than using only pairs of variables found in complete data cases. Correlations were computed between variables for each cruise separately. All statistical analyses were performed by existing computer programs found in the University of Michigan statistical software package, MIDAS (Michigan Interactive Data Analysis System).

Factor analyses were run using the correlation matrices from each cruise. The number of factors extracted was based on the somewhat arbitrary criterion that only factors with eigenvalues greater than or equal to 1.00 should be used (Rummel, 1970). The values of the communalities for each variable were estimated using the iterative principal axis factor solution as described in Harman (1967). Convergence of communalities was deemed sufficient when succeeding estimates differed by less than 1.0×10^{-3} or after twenty iterations. An orthogonal varimax rotation was performed on the factor matrix.

In addition to the correlation analyses, cluster analysis was used to graphically display the similarity between sampling stations. The approach was similar to the Straits of Mackinac analysis (Moll et al., 1976), in that data from one depth of one cruise were clustered and these clusters then circled on a map of the sampling stations. The clustering techniques were identical to those used in the Straits of Mackinac analysis: euclidean distances were calculated between all sets of variables, and these distances were then clustered using an average weighted algorithm (UPGMA) (Sneath and Sokal, 1973). The only associations that were considered in the cluster analysis were those in the lower half of the hierarchy based on the number of branchings. In other words, only the closely related clusters were considered. This hierarchy was displayed by circling the clusters of stations on a map of the sampling area.

RESULTS

Correlation Analysis

The correlations were initially calculated on a cruise-by-cruise basis to look for changes in the relationships of variables to one another throughout the 1974 sampling season. Data from the first cruise (April 1974) were not analyzed because the number of stations sampled and the number of variables measured were considerably fewer than on the other cruises.

The second cruise (May 14-17) occurred when a thermal bar was found close along the shore. The thermal bar is a condition created by warming of the lake from the shore toward the center (Boyce, 1974). Thus, a band of warm water is found along the shore, while the center of the lake remains cold. The correlation matrix from this cruise (Table 4.1) reflects the thermal bar condition; almost all correlations were high, indicating the well mixed, unstratified water column beyond the thermal bar in the center of the lake. The spring diatom bloom was evident between the thermal bar and the shore (Stoermer and Kreis, In press) contributing to the high correlation between ^{14}C uptake (primary production) and chlorophyll a. Diatom growth appears to have been sufficiently advanced to reduce silica levels (Section 3) such that correlations between soluble silica and chlorophyll a and ^{14}C uptake were highly negative.

The factor analysis of the cruise 2 data separated the data into three factors (Table 4.2). These factors are:

1) Open lake water with high loadings for temperature, silica, Secchi depth, pH, and chlorophyll a (Secchi depth and silica negative),

2) water between the thermal bar and the shore with high loadings for particulate silica, total phosphorus, nitrate nitrogen, silica, and Secchi depth silica and Secchi disc negative),

3) Saginaw Bay water with high loadings for chloride, total phosphorus, and chlorophyll a.

Between cruises 2 (May 14-17) and 3 (June 4-8), a period of rapid spring warming occurred in that surface water temperatures <4° C were not observed in the survey area. Similar to cruise 2, the correlations from cruise 3 showed that many variables were highly correlated (Table 4.3). Although the majority of stations sampled were in stratified water, most of the samples came from hypolimnetic waters in that the newly formed epilimnion represented only a small volume of southern Lake Huron.

Sufficient phytoplankton growth occurred between the mid-May and early June cruises to change the relationships between many of the measured variables. These changes are evident by comparing the correlation matrices from cruises 2 and 3; many of the correlations among nutrients were lower during cruise 3. An example is the change in the chlorophyll a silica correlation from -0.829 in mid-May to -0.308 in early June. The largest shifts in correlations involved correlations among temperature, chlorophyll a, and Secchi depth.

The factor solution for cruise 3 (Table 4.2) was similar to cruise 2 in that three factors were extracted and ammonia had a very low communality. The three factors are:

TABLE 4.1. CORRELATION MATRIX FROM CRUISE 2

VARIAB	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO
SECCHI	1.0000													
TEMP	-.7444 (189)	1.0000												
PH	-.3868 (189)	.7254 (192)	1.0000											
CHLOR	-.6465 (188)	.7603 (191)	.6270 (191)	1.0000										
SIO2	.7712 (173)	-.7637 (176)	-.5899 (176)	-.8289 (175)	1.0000									
NO3	-.5886 (172)	.3359 (175)	.1924 (175)	.6467 (174)	-.5992 (175)	1.0000								
NH3	.0431 (189)	.1112 (192)	.1544 (192)	.2080 (191)	-.0333 (176)	.1032 (175)	1.0000							
TPO4	-.6123 (186)	.5232 (189)	.3102 (189)	.6735 (188)	-.6523 (173)	.7887 (172)	.1020 (189)	1.0000						
COND	-.5942 (189)	.5741 (192)	.5642 (192)	.7108 (191)	-.6794 (176)	.5652 (175)	.0038 (192)	.5345 (189)	1.0000					
ALK	-.6649 (44)	.4821 (45)	.2402 (45)	.5203 (45)	-.6329 (42)	.5532 (42)	.1725 (45)	.5634 (45)	.5030 (45)	1.0000				
C-14	-.7918 (44)	.6750 (45)	.3864 (45)	.8402 (45)	-.7895 (42)	.8732 (42)	.2642 (45)	.9054 (45)	.6990 (45)	.6171 (45)	1.0000			
CL	-.5170 (189)	.6660 (192)	.6487 (192)	.8540 (191)	-.7600 (176)	.5714 (175)	.1859 (192)	.5353 (189)	.7545 (192)	.4056 (45)	.6069 (45)	1.0000		
SO4	-.4297 (189)	.5574 (192)	.4895 (192)	.7693 (191)	-.6951 (176)	.6272 (175)	.1030 (192)	.5563 (189)	.5761 (192)	.4579 (45)	.6710 (45)	.8343 (192)	1.000	
PSIO	-.7046 (188)	.4781 (191)	.1675 (191)	.5686 (190)	-.5950 (175)	.7118 (174)	.0136 (191)	.8225 (188)	.4313 (191)	.5380 (45)	.7726 (45)	.2762 (191)	.3375 (191)	1.000

TABLE 4.2. FACTOR ANALYSIS OF 12 VARIABLES MEASURED DURING 1974 CRUISES IN SOUTHERN LAKE HURON

CRUISE 2		Factor		
		1	2	3
% Variation Explained		24.9	29.6	20.3
Variable	**Communality**	**Factor Loadings**		
Secchi disc	.801	-.660	-.604	.009
Temperature	.879	.843	.289	.292
pH	.614	.657	-.004	.426
Chlorophyll	.888	.531	.505	.592
SiO_2	.812	-.640	-.515	-.369
NO_3	-.893	-.097	-.849	-.403
NH_3	.051	.037	-.004	.223
$T-PO_4$	.828	.230	.826	.294
Conductivity	.600	.502	.387	.446
Chloride	.980	.499	.251	.817
SO_4	.732	.278	.376	.716
$P-SiO_2$	.910	.265	.912	-.088

CRUISE 3		Factor		
		1	2	3
% Variation Explained		30.9	18.6	9.6
Variable	**Communality**	**Factor Loadings**		
Secchi disc	.820	-.430	-.686	.405
Temperature	.553	-.648	.130	-.340
pH	.896	.633	-.115	-.694
Chlorophyll	.343	.117	.529	-.224
SiO_2	.825	-.780	-.326	.333
NO_3	.397	.075	.532	.328
NH_3	.057	.021	-.043	.234
$T-PO_4$	.152	.358	.113	-.104
Conductivity	.625	.737	.233	.166
Chloride	.698	.834	.050	.006
SO_4	.734	.818	.195	-.166
$P-SiO_2$	.990	.200	.974	-.017

TABLE 4.3. CORRELATION MATRIX FROM CRUISE 3

VARIABLE	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO
SECCHI	1.0000													
TEMP	-.5137 (236)	1.0000												
PH	-.4955 (236)	.6308 (236)	1.0000											
CHLOR	-.5422 (234)	.0797 (234)	.1828 (234)	1.0000										
SIO2	.6718 (235)	-.8647 (235)	-.6431 (235)	-.3081 (233)	1.0000									
NO3	-.3160 (235)	.1148 (235)	-.2815 (235)	.0407 (233)	-.2220 (234)	1.0000								
NH3	.1846 (233)	-.1051 (233)	-.1289 (233)	-.0169 (231)	.1502 (232)	-.0450 (232)	1.0000							
TPO4	-.2768 (224)	.1982 (224)	.2917 (224)	.0847 (222)	-.2521 (223)	-.0126 (223)	.0256 (221)	1.0000						
COND	-.4327 (236)	.4042 (236)	.3132 (236)	.1980 (234)	-.5865 (235)	.2768 (235)	.0033 (233)	.2078 (224)	1.0000					
ALK	-.7124 (57)	.6845 (57)	.5983 (57)	.2827 (57)	-.7777 (57)	.3265 (56)	.0959 (56)	.5141 (55)	.5688 (57)	1.0000				
C-14	-.5648 (58)	.4596 (58)	.6489 (58)	.4370 (58)	-.6818 (58)	.0943 (57)	-.0058 (57)	.3985 (56)	.6908 (58)	.5347 (57)	1.0000			
CL	-.4165 (226)	.5011 (226)	.5673 (226)	.1766 (224)	-.6118 (225)	.0603 (225)	.0208 (226)	.3272 (214)	.6567 (226)	.6129 (55)	.6432 (56)	1.0000		
SO4	-.5692 (233)	.5868 (233)	.5771 (233)	.3058 (231)	-.7362 (232)	.0921 (232)	-.1501 (233)	.3371 (221)	.6275 (233)	.6743 (56)	.6270 (57)	.7485 (226)	1.000	
PSIO	-.6997 (234)	.3047 (234)	.0446 (234)	.5953 (232)	-.5013 (233)	.5852 (233)	.0144 (231)	.1461 (222)	.3373 (234)	.5516 (57)	.4321 (58)	.2391 (224)	.3671 (231)	1.000

1) Nearshore water with high loadings for chloride, conductivity, sulfate, pH, and silica (negative loading),

2) offshore waters with high loadings for particulate silica, nitrate-nitrogen, and temperature (negative loading),

3) hypolimnetic waters with high temperature and pH loadings.

Surface waters continued to warm between cruises 3 (June 4-7) and 4 (June 17-21). The relationship among variables continued to change as thermal stratification developed further and plankton growth proceeded in the surface waters. The largest changes in correlations among variables from cruise 3 to cruise 4 involved chlorophyll a, temperature, pH, ammonia, and total phosphorus (Table 4.4). The chlorophyll a to ^{14}C uptake correlation increased from +0.437 in early June to +0.794 by mid-June; the reason for this increase is not apparent.

The factor solution for cruise 4 (Table 4.5) again yielded three factors. This solution produced factors for the same three water types as did the cruise 3 solution, but the ammonia communality vastly increased. These factors are:

1) Nearshore and Saginaw Bay water with high loadings for ammonia, chloride, total soluble phosporus, sulfate, and total phosphorus,

2) hypolimnetic water with high loadings for temperature, pH, and silica (negative loading),

3) offshore epilimnetic waters with high loadings for particulate silica, chlorophyll a, and Secchi disc (negative loading).

The fifth cruise (July 17-21) occurred during typical summer thermal stratification with a well developed 15-20 m thermocline (Section 3). The depletion of nutrients in the epilimnion had apparently caused a lowering of the level of ^{14}C uptake and a shift in the plankton crop from mid-June. These events were reflected in the decrease in the correlation between particulate silica, ^{14}C uptake, chlorophyll a and silica (Table 4.6). The high correlations between temperature and nutrients observed throughout the first four cruises were absent from the cruise 5 correlation matrix, a further indication of epilimnetic nutrient depletion.

The factor analysis for cruise 5 yielded three factors (Table 4.5). These factors were identified with the same three water types as the solutions from earlier cruises, but, the factors for Saginaw Bay are now the least important of the three (smallest sums of squares) rather than the most important. The cruise 5 factors are:

1) Hypolimnetic water with high loadings for silica, nitrate nitrogen, temperature, and pH (negative loadings for the nutrients),

2) epilimnetic water high loadings for chlorophyll a, particulate silica, total phosphorus, and conductivity,

TABLE 4.4. CORRELATION MATRIX FROM CRUISE 4

VARIABLE														
SECCHI	1.0000													
TEMP	-.5812 (222)	1.0000												
PH	-.1676 (222)	.3968 (222)	1.0000											
CHLOR	-.5600 (222)	.3238 (222)	.0431 (222)	1.0000										
SIO2	.6393 (222)	-.8384 (222)	-.3993 (222)	-.5579 (222)	1.0000									
NO3	-.4999 (215)	.1985 (215)	-.0066 (215)	.2708 (215)	-.1944 (215)	1.0000								
NH3	-.4022 (200)	.3617 (200)	-.1318 (200)	.3225 (200)	-.3522 (200)	.4674 (197)	1.0000							
TPO4	-.5977 (210)	.4838 (210)	.0172 (210)	.5720 (210)	-.6160 (210)	.2745 (204)	.6613 (190)	1.0000						
COND	-.5245 (222)	.4551 (222)	.0077 (222)	.5016 (222)	-.6133 (222)	.1915 (215)	.6689 (200)	.7378 (210)	1.0000					
ALK	-.4491 (56)	.2869 (56)	-.1593 (56)	.3837 (56)	-.4768 (56)	.0640 (53)	.3627 (48)	.5826 (55)	.5354 (56)	1.0000				
C-14	-.6299 (56)	.5392 (56)	-.0073 (56)	.7937 (56)	-.7348 (56)	.2534 (53)	.7445 (48)	.8034 (55)	.7765 (56)	.5118 (56)	1.0000			
CL	-.5899 (215)	.6282 (215)	.0118 (215)	.4809 (215)	-.6857 (215)	.3853 (213)	.7909 (199)	.8020 (204)	.8388 (215)	.4647 (54)	.7532 (54)	1.0000		
SO4	-.5708 (218)	.6267 (218)	.0507 (218)	.4554 (218)	-.6579 (218)	.2949 (212)	.6930 (197)	.7285 (207)	.8127 (218)	.4509 (56)	.6921 (56)	.9054 (212)	1.000	
PSIO	-.6772 (220)	.4322 (220)	.1304 (220)	.7560 (220)	-.5742 (220)	.3351 (213)	.2981 (198)	.5657 (208)	.5494 (220)	.3994 (56)	.6626 (56)	.4652 (213)	.4801 (216)	1.000
	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO

TABLE 4.5. FACTOR ANALYSIS OF 12 VARIABLES MEASURED DURING 1974 CRUISES IN SOUTHERN LAKE HURON

CRUISE 4		Factor		
		1	2	3
% Variation Explained		34.4	14.2	21.8
Variable	**Communality**		**Factor Loadings**	
Secchi disc	.644	-.362	-.339	-.631
Temperature	.827	.424	.778	.205
pH	.305	-.144	.530	.062
Chlorophyll	.688	.310	.149	.755
SiO_2	.900	-.435	-.724	-.431
NO_3	.208	.295	.048	.344
NH_3	.692	.805	-.061	.201
$T\text{-}PO_4$	.731	.723	.148	.431
Conductivity	.748	.789	.074	.347
Chloride	.996	.940	.200	.268
SO_4	.823	.842	.202	.271
$P\text{-}SiO_2$	.885	.196	.200	-.898

CRUISE 5		Factor		
		1	2	3
% Variation Explained		22.3	21.9	17.3
Variable	**Communality**		**Factor Loadings**	
Secchi disc	.582	-.494	-.490	-.313
Temperature	.757	-.723	-.351	.333
pH	.360	.569	.107	.157
Chlorophyll	.656	-.166	.792	-.036
SiO_2	.900	-.930	.172	-.075
NO_3	.398	-.619	.087	-.080
NH_3	.476	-.210	.485	.444
$T\text{-}PO_4$	.484	.141	.589	.342
Conductivity	.577	.132	.591	.454
Chloride	.798	.306	.100	.834
SO_4	.689	.255	.089	.785
$P\text{-}SiO_2$	.707	-.256	.801	-.029

TABLE 4.6. CORRELATION MATRIX FROM CRUISE 5

VARIABLE														
SECCHI	1.0000													
TEMP	-.4323 (229)	1.0000												
PH	-.3068 (229)	.3476 (229)	1.0000											
CHLOR	-.2841 (228)	-.4578 (228)	.0037 (228)	1.0000										
SIO2	.4037 (229)	-.7496 (229)	-.6207 (229)	.2761 (228)	1.0000									
NO3	.3596 (222)	-.5018 (222)	-.2243 (222)	.1261 (221)	.4474 (222)	1.0000								
NH3	-.3935 (199)	-.1443 (199)	-.0597 (199)	.3208 (198)	.2627 (199)	.1449 (193)	1.0000							
TPO4	-.4218 (227)	-.0214 (227)	.1754 (227)	.5073 (226)	-.0409 (227)	-.1156 (220)	.3411 (197)	1.0000						
CCND	-.4092 (225)	-.0781 (225)	.2574 (225)	.4561 (224)	.0555 (225)	-.1266 (218)	.5259 (195)	.4949 (223)	1.0000					
ALK	-.2851 (57)	.4065 (57)	.0329 (57)	.2916 (57)	-.2684 (57)	-.3902 (53)	-.0744 (46)	.3687 (57)	.2904 (56)	1.0000				
C-14	-.5395 (57)	.4425 (57)	.3994 (57)	.8779 (57)	-.2687 (57)	-.4597 (53)	.3002 (46)	.6796 (57)	.6638 (56)	.2575 (57)	1.0000			
CL	-.4757 (223)	.4466 (223)	.3125 (223)	.0985 (222)	-.3652 (223)	-.2494 (222)	.3294 (194)	.4074 (221)	.4517 (219)	.2115 (53)	.6480 (53)	1.0000		
SO4	-.3828 (220)	.4158 (220)	.3857 (220)	.0449 (219)	-.3541 (220)	-.0869 (219)	.3238 (193)	.3142 (218)	.3812 (216)	.0348 (52)	.5420 (52)	.7465 (220)	1.000	
FSIO	-.3341 (225)	-.4486 (225)	-.0618 (225)	.6883 (224)	.3086 (225)	.2651 (218)	.4419 (195)	.4094 (223)	.3489 (221)	.1529 (56)	.3684 (56)	-.0260 (219)	.0308 (216)	1.000
	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO

3) Saginaw Bay water with high loadings for chloride and sulfate.

Nutrient depletion in the epilimnion was particularly evident during cruise 6 (August 26-31). Water temperatures approached their annual maximum while nutrients, silica in particular, reached their annual minimum. This highly stratified condition resulted in a slight lowering of all correlations among variables on cruise 6 (Table 4.7). The correlations between particulate silica, ^{14}C uptake, and chlorophyll a were lower in August than in July, while the correlation between silica and ^{14}C uptake went from negative to positive. Despite the five weeks between cruises 5 and 6, the change in correlations among the different variables changed less than between other cruises.

Only two factors were extracted from the factor analysis for cruise 6 (Table 4.8) and these were attributed to hypolimnetic and epilimnetic waters. Saginaw Bay water was apparently mixed into the epilimnion and circulating throughout the southern half of Lake Huron. The moderately high chloride loading on the epilimnion (second) factor would support this hypothesis. The cruise 6 factors are:

1) Hypolimnetic water with high particulate silica, conductivity, pH, and temperature loadings (pH and temperature negative loadings),

2) epilimnetic waters with high chlorophyll a and total phosphorus loadings.

Significant cooling and mixing had occurred during the month between cruise 6 (August 26-31) and cruise 7 (October 8-12), dropping surface temperatures to 10-20°C and lowering the thermocline to 40 m. The cooling and mixing induced several changes in the correlations among variables from cruise 6 to cruise 7 (Tables 4.7 and 4.9). A large increase was observed in the correlations between chlorophyll a and silica and chlorophyll a and nitrate-nitrogen. The correlation between silica and ^{14}C uptake went from positive to negative. Some of the changes in the correlations between cruises 6 and 7 were most likely precipitated by a shift in phytoplankton assemblages from summer to fall (Stoermer and Kreis, In press).

The factor solution for cruise 7 (Table 4.8) was composed of three factors. Although the factor solution separated the lake into hypolimnetic and epilimnetic waters as in cruise 6, the communalities in the cruise 7 solution were higher. These higher communalities imply an overall higher interrelationship of the variables to one another (Mulaik, 1972), perhaps a result of the well-mixed water column. The cruise 7 factors are:

1) Epilimnetic waters with high chlorophyll a, total phosphorus, chloride, Secchi disc, and nitrate nitrogen loadings (Secchi disc and nitrate nitrogen negative loadings),

2) hypolimnetic water with high temperature and silica loadings (silica a negative loading),

TABLE 4.7. CORRELATION MATRIX FROM CRUISE 6

VARIABLE	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C14	CL	SO4	PSIO
SECCHI	1.0000													
TEMP	-.1413 (257)	1.0000												
PH	-.1776 (257)	.7804 (257)	1.0000											
CHLOR	-.4234 (252)	-.1991 (252)	-.0614 (252)	1.0000										
SIO2	.1051 (254)	-.7042 (254)	-.8367 (254)	.2128 (249)	1.0000									
NO3	.3870 (107)	-.6794 (107)	-.7345 (107)	-.0085 (104)	.5745 (106)	1.0000								
NH3	.0290 (221)	-.3327 (221)	-.1779 (221)	.1708 (217)	.2793 (220)	.2229 (105)	1.0000							
TPO4	-.2532 (245)	-.0701 (245)	.0209 (245)	.5508 (241)	.1484 (243)	-.1002 (100)	.1424 (211)	1.0000						
COND	-.0574 (257)	-.7856 (257)	-.6483 (257)	.3814 (252)	.6626 (254)	.5273 (107)	.3703 (221)	.1935 (245)	1.0000					
ALK	-.4997 (65)	-.2720 (65)	.5062 (65)	.4628 (64)	-.0681 (64)	-.2754 (28)	-.2635 (54)	.3386 (60)	.5639 (65)	1.0000				
C14	-.5110 (65)	-.0201 (65)	.5525 (65)	.9270 (64)	.2436 (64)	-.6969 (28)	.4319 (54)	.6872 (60)	.7376 (65)	.3504 (65)	1.0000			
CL	-.2852 (256)	.1757 (256)	.2115 (256)	.3795 (251)	-.0820 (253)	-.2214 (107)	-.0158 (220)	.3167 (244)	.0374 (256)	.3463 (65)	.8192 (65)	1.0000		
SO4	-.1759 (106)	.1635 (106)	.1568 (106)	.1028 (102)	-.0924 (106)	-.0549 (104)	-.1309 (103)	.1311 (98)	-.1111 (106)	.1992 (28)	-.1030 (28)	.0898 (106)	1.000	
PSIO	-.1177 (257)	-.4692 (257)	-.4942 (257)	.3825 (252)	.4806 (254)	.5243 (107)	.2103 (221)	.1275 (245)	.4639 (257)	.2220 (65)	.1884 (65)	-.0980 (256)	.0563 (106)	1.000

TABLE 4.8. FACTOR ANALYSIS OF 12 VARIABLES MEASURED DURING 1974 CRUISES IN SOUTHERN LAKE HURON

CRUISE 6		Factor	
		1	2
% Variation Explained		34.9	18.0
Variable	**Communality**	**Factor Loadings**	
Secchi disc	.255	.072	-.500
Temperature	.812	-.886	.133
pH	.842	-.878	.267
Chlorophyll	.847	.278	.877
SiO_2	.724	.847	-.080
NH_3	.120	.327	.115
$T\text{-}PO_4$	.387	.182	.595
Conductivity	.694	.814	.179
Chloride	.244	-.116	.480
$P\text{-}SiO_2$	.373	.567	.227

CRUISE 7		Factor		
		1	2	3
% Variation Explained		34.5	19.2	7.2
Variable	**Communality**	**Factor Loadings**		
Secchi disc	.585	-.659	-.356	-.155
Temperature	.917	-.064	.934	.199
pH	.478	.119	-.032	-.681
Chlorophyll	.623	.713	.304	-.146
SiO_2	.841	-.241	-.882	.061
NO_3	.855	-.835	-.397	.010
NH_3	.202	.071	.312	.316
$T\text{-}PO_4$	.768	.832	.045	-.270
Conductivity	.533	.663	-.251	-.172
Chloride	.854	.917	.115	-.018
SO_4	.334	.511	.090	.253
$P\text{-}SiO_2$	.313	.430	.304	.188

TABLE 4.9. CORRELATION MATRIX FROM CRUISE 7

VARIABLE														
SECCHI	1.0000													
TEMP	-.4034 (192)	1.0000												
PH	.0008 (192)	-.1272 (192)	1.0000											
CHLOR	-.5533 (183)	.2977 (183)	.1862 (183)	1.0000										
SIC2	.4258 (190)	-.8596 (190)	-.0366 (190)	-.4438 (181)	1.0000									
NO3	.6812 (183)	-.4100 (183)	-.0105 (183)	-.7887 (174)	.5579 (182)	1.0000								
NH3	-.1645 (190)	.3205 (190)	-.1727 (190)	.1205 (181)	-.2185 (189)	-.1106 (182)	1.0000							
TPC4	-.5286 (191)	.0734 (191)	.2498 (191)	.6542 (182)	-.2713 (189)	-.7285 (182)	-.0369 (189)	1.0000						
COND	-.3390 (192)	-.1961 (192)	.1729 (192)	.3900 (183)	.0878 (190)	-.5093 (183)	-.1335 (190)	.5722 (191)	1.0000					
ALK	-.2479 (51)	-.2937 (51)	.3963 (51)	.2837 (48)	.0296 (51)	-.4216 (51)	-.1756 (51)	.4184 (51)	.3578 (51)	1.0000				
C-14	-.6331 (51)	-.0717 (51)	.2032 (51)	.8843 (48)	-.4694 (51)	-.9544 (51)	-.0146 (51)	.9248 (51)	.7761 (51)	.4437 (51)	1.0000			
CL	-.5931 (190)	.1942 (190)	.0621 (190)	.6809 (181)	-.3318 (189)	-.7674 (182)	.0505 (189)	.7712 (189)	.5672 (190)	.3584 (50)	.8957 (50)	1.0000		
SO4	-.3814 (189)	.1729 (189)	-.1999 (189)	.3182 (180)	-.2141 (188)	-.5399 (182)	.0634 (188)	.4057 (188)	.2922 (189)	.2652 (51)	.5856 (51)	.6000 (188)	1.000	
PSIO	-.6285 (191)	.3235 (191)	-.0237 (191)	.3858 (182)	-.3279 (190)	-.3880 (183)	.2119 (190)	.3470 (190)	.1984 (191)	-.0326 (51)	.3036 (51)	.4475 (190)	.2101 (189)	1.000
	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO

3) the third factor had no apparent significance.

Cruise 8 in mid-November (November 10-14) was conducted when the water column was mixed to 50 m. There were few large changes in the correlation coefficients between cruises 7 and 8, although the correlations between variables were generally higher for cruise 8 than during the summer (Table 4.10). The correlation matrix for cruise 8 was somewhat similar to the matrices of cruises 2 and 3. This similarity was interpreted as a return toward non-stratified conditions in southern Lake Huron. The correlations for cruises 6 and 7 indicate nutrient replenishment in the surface waters had begun during cruise 6 but was not complete by November.

Four factors were extracted from the cruise 8 solution with the communalities somewhat higher than the summer cruise solutions (Table 4.11). The four factors identified three types of water. The three water types are:

1) Open lake epilimnetic water with high loadings for Secchi depth, chlorophyll _a_, and particulate silica (chlorophyll _a_ and particulate silica negative),

2) nearshore and Saginaw Bay water with high chloride, sulfate, and total phosphorus loadings,

3) hypolimnetic waters on two factors (3 and 4) with high loadings for silica, nitrate nitrogen, pH, chlorophyll _a_, and temperature.

Cluster Analysis

Similar to the Straits of Mackinac analysis, station-to-station relationships were analyzed with cluster analysis (Moll et al., 1976). The results were not as useful in defining water mass relationships in southern Lake Huron as they were for the Straits area. Areas of similar water quality were often observed on opposite shores of the lake and long, meaningless lines were necessary to connect stations of one cluster. As a result of this unsatisfactory solution from the cluster analysis, a different technique was pursued and is discussed in Section 5.

DISCUSSION

Nutrient Succession

Schelske and Stoermer (1971), Schelske et al. (1972), Kilham (1971), Munawar and Burns (1976), and others have pointed out the importance of differential uptake of nutrients in phytoplankton annual succession. By the same token, differential regeneration rates of nutrients have a profound effect on plankton species succession (Schelske and Stoermer, 1971; Schelske et al., 1974; Lean, 1973). The sampling program for 1974 showed offshore southern Lake Huron displayed nutrient depletion typical of oligotrophic or nutrient-poor waters. An analysis was conducted of the changes in nutrient ratios in southern Lake Huron during the summer of 1974. This analysis provided several insights into phytoplankton growth strategy, and these insights are presented below.

TABLE 4.10. CORRELATION MATRIX FROM CRUISE 8

VARIABLE														
SECCHI	1.0000													
TEMP	-.1601 (229)	1.0000												
PH	-.2046 (229)	.1933 (229)	1.0000											
CHLOR	-.5998 (227)	-.0200 (227)	.3781 (227)	1.0000										
SIO2	.3356 (226)	-.5368 (226)	-.4310 (226)	-.3903 (224)	1.0000									
NO3	.3933 (221)	-.2884 (221)	-.2838 (221)	-.5812 (219)	.5263 (220)	1.0000								
NH3	.1055 (219)	.0299 (219)	-.0237 (219)	-.0237 (217)	.0292 (219)	.1179 (214)	1.0000							
TPO4	-.2382 (222)	.0601 (222)	.0216 (222)	.2001 (220)	-.1562 (219)	-.1741 (214)	-.0076 (213)	1.0000						
COND	-.3590 (229)	-.1935 (229)	.2097 (229)	.3747 (227)	-.2552 (226)	-.1718 (221)	-.0318 (219)	.2892 (222)	1.0000					
ALK	-.0029 (59)	-.1776 (59)	-.0835 (59)	.3135 (59)	-.3524 (58)	-.5230 (57)	.1464 (57)	.0848 (59)	.1817 (59)	1.0000				
C-14	-.4307 (59)	-.4008 (59)	.1878 (59)	.7969 (59)	-.3661 (58)	-.7231 (57)	.1482 (57)	.4613 (59)	.5040 (59)	.5325 (59)	1.0000			
CL	-.2397 (222)	.1093 (222)	.0153 (222)	.2636 (220)	-.1873 (221)	-.1123 (221)	.0868 (215)	.3962 (215)	.4110 (222)	.0356 (57)	.5469 (57)	1.0000		
SO4	-.0661 (222)	.2517 (222)	-.0064 (222)	-.0989 (220)	-.1081 (222)	.0729 (220)	.0741 (215)	.2798 (215)	.0691 (222)	-.1762 (57)	-.2424 (57)	.5731 (221)	1.000	
ESIO	-.6557 (228)	.0831 (228)	.2406 (228)	.5452 (226)	-.2774 (225)	-.2734 (220)	-.1181 (218)	.2035 (221)	.2228 (228)	.0535 (59)	.2602 (59)	.1561 (221)	.0483 (221)	1.000
	SECCHI	TEMP	PH	CHLOR	SIO2	NO3	NH3	TPO4	COND	ALK	C-14	CL	SO4	PSIO

TABLE 4.11. FACTOR ANALYSIS OF 12 VARIABLES MEASURED DURING 1974 CRUISES IN SOUTHERN LAKE HURON

CRUISE 8		Factor			
		1	2	3	4
% Variation Explained		13.1	9.6	9.6	17.5
Variable	Communality	Factor Loadings			
Secchi disc	.723	.749	-.248	.022	-.315
Temperature	.906	.016	.107	-.885	.335
pH	.277	-.151	-.030	-.092	.494
Chlorophyll	.741	-.507	.140	.243	.636
SiO_2	.651	.131	-.164	.336	-.703
NO_3	.592	.234	-.073	.037	-.728
NH_3	.035	.161	.079	-.028	-.041
$T\text{-}PO_4$	.257	-.149	.468	.032	.123
Conductivity	.396	-.186	.378	.327	.334
Chloride	.835	.018	.903	.041	.135
SO_4	.529	.070	.655	-.275	-.139
$P\text{-}SiO_2$	.641	-.759	.152	-.038	.202

Table 4.12 shows the mean concentrations of four nutrients measured in central southern Lake Huron. The seasonal pattern of these four nutrients was similar to patterns observed in other Great Lakes (Schelske et al., 1975; Burns, 1976). Silica and nitrate nitrogen, with their slow regeneration rates, steadily decreased throughout the summer. Ammonia peaked in mid-June (cruise 4) when zooplankton activity was maximal, and total soluble phosphorus concentrations remained near the limit of detection throughout the summer. The phytoplankton community in Lake Huron has developed a strategy which accommodates the seasonal patterns of nutrient succession. Diatoms and certain chrysophytes which require silica for growth are most productive early in the summer when silica levels are at their highest. But plankton that require silica for growth may not have a large competitive advantage if they developed an ability to take up ammonia over nitrate as a nitrogen source. The reason these silica-requiring species may not have an enhanced ability to take up ammonia over nitrate is that nitrate levels are normally high when silica is also high. Ammonia, on the other hand, is not particularly abundant in the spring when silica levels are not limiting for diatom growth; ammonia is normally most abundant during the mid-summer (Table 4.15), when silica levels are becoming limiting for those phytoplankton which require silica (Schelske and Stoermer, 1971). Organisms which do not require silica but require nitrogen and phosphorus face a different scheme. The ratio of soluble phosphorus relative to nitrate nitrogen was low in June and July, times when high growth is possible because of high light intensity (Table 4.15). On the other hand, ammonia concentrations appeared highest during June of 1974. Analysis of trends in the growth of individual phytoplankton species by Stoermer and Kreis (In press) for southern Lake Huron in 1974 showed non-silica requiring phytoplankton followed the ammonia peak. In 1975, a study was conducted comparing phytoplankton dynamics in Lake Huron to dynamics in Saginaw Bay, an area where normal seasonal nutrient succession is disrupted by eutrophication. The results of this study are presented in Section 6.

Phytoplankton Successional Events

Phytoplankton succession in southern Lake Huron was carefully monitored during the summer of 1974 (Stoermer and Kreis, In press). The correlation analysis of nutrient succession (Fig. 4.2) showed that major shifts in phytoplankton crop (observed by Stoermer and Kreis, In press) could be related to changes in silicon form (from soluble silica to particulate silica) and concentration. In addition, the correlations between silica, ^{14}C uptake, and chlorophyll a also indicated a shift in algal crop.

The correlation and factor analyses reflect the changes in relationships between nutrients and other variables throughout the summer of 1974. Some of the changes can be interpreted as differential uptake of one nutrient, although cause and effect cannot be inferred from correlations. The period of most rapid change in correlations was between cruises 3 and 5, during the onset of thermal stratification. The correlations among soluble and particulate silica, chlorophyll a, and ^{14}C uptake confirms the rapid changes between cruises 3 and 5. Figure 4.3 shows that while the ^{14}C uptake to particulate silica and chlorophyll a to particulate silica correlations change little throughout the summer, this is not true for correlations with

TABLE 4.12. MEAN CONCENTRATIONS AND STANDARD ERRORS OF FOUR NUTRIENTS FROM SOUTHERN LAKE HURON, 1974

	Soluble Silica (mg SiO_2/l)	Nitrate (μg N/l)	Ammonia (μg N/l)	Total Soluble Phosphorus (μg P/l)
Cruise 1	1.86 ± .03	348 ± 8.2	11.9 ± .40	2.48 ± .12
Cruise 2	1.17 ± .02	348 ± 6.0	12.8 ± .22	2.51 ± .06
Cruise 3	1.26 ± .03	306 ± 3.1	10.4 ± .38	3.33 ± .14
Cruise 4	1.21 ± .02	339 ± 3.5	25.9 ± 1.6	3.25 ± .12
Cruise 5	1.06 ± .02	291 ± 2.4	12.4 ± .54	2.49 ± .09
Cruise 6	1.03 ± .03	299 ± 4.0	8.8 ± .32	2.99 ± .14
Cruise 7	0.72 ± .01	241 ± 3.7	5.0 ± .25	2.53 ± .11
Cruise 8	1.03 ± .02	261 ± 2.9	8.57 ± .52	3.81 ± .20

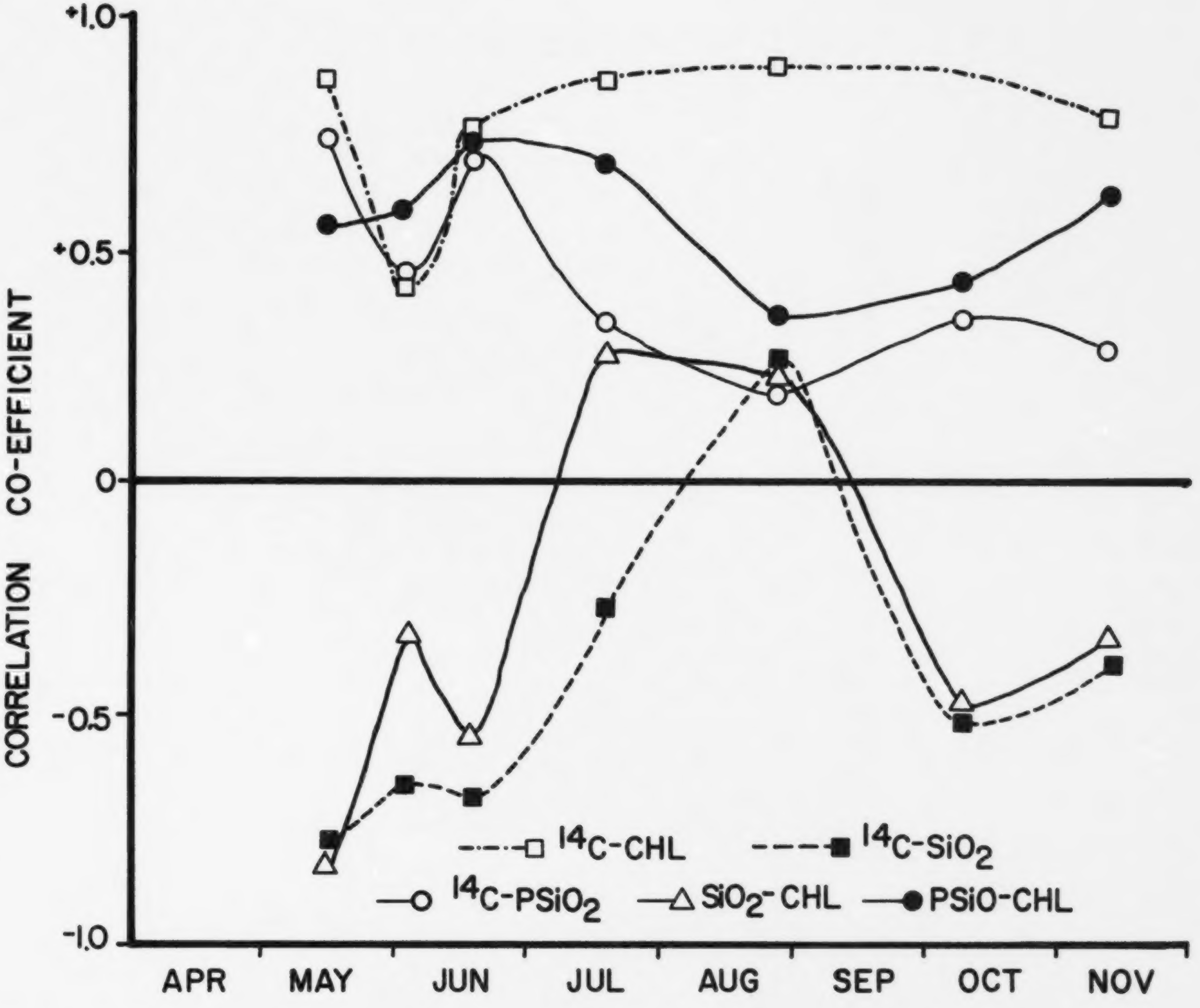

Figure 4.2. Correlation trends.

soluble silica. These results can be interpreted as follows: the relative proportion of chlorophyll a biomass containing particulate silica did not change dramatically throughout the sampling season (particulate silica to chlorophyll a correlations ranged from +0.756 to +0.383). But, the proportion of ^{14}C uptake associated with particulate silica changed considerably (particulate silica to ^{14}C uptake correlation ranged from +0.773 to +0.188). The inference is that the fraction of chlorophyll a containing particulate silica contributed only a small amount to the ^{14}C uptake pool by late summer of 1974. The chlorophyll a to ^{14}C uptake correlations change very little throughout the entire sampling season.

The correlations among soluble silica, chlorophyll a, and ^{14}C uptake changed much more than did correlations with particulate silica. The correlations between soluble silica and chlorophyll a were large and negative early in the summer of 1974, but by July were small and positive. The ^{14}C uptake to soluble silica correlations follow a similar pattern, moving from large and negative to small and positive. The inference from these results is not clear. Prior research indicates that diatoms predominate in the late spring and early summer (Schelske and Stoermer, 1971). The results from Lake Huron seem to confirm those earlier studies; in the early summer productivity and biomass are high, silica levels are low and rapidly decreasing. By mid-summer, soluble silica levels are very low and much less tied to ^{14}C uptake and chlorophyll a concentrations implying more production by non-silica requiring species.

Several aspects of the sampling program may place a limit on the validity of the results discussed above. The ^{14}C uptake values during all the Lake Huron cruises came from 1 to 5 m samples and were incubated on-deck in an artificial light incubator. A better understanding of phytoplankton successional events may be possible with *in situ* ^{14}C uptake profiles that include samples from the deep chlorophyll layer, normally a major portion of summer phytoplankton ecology in the Great Lakes (Moll, 1978).

General Limnological Succession

The sampling frequency in 1974 (at least one cruise per month except September) allowed an analysis of limnological succession from thermocline formation to fall mixing. The limnology of Lake Huron was dominated in the spring of 1974 by the thermal bar. The thermal bar had the effect of holding the high nutrient runoff water nearshore (Section 7). This effect was particularly interesting in that Saginaw Bay water, readily identified by high chloride content, was prevented from mixing with open lake water by the thermal bar. The cruise 2 factor analysis showed the most important factor was for thermal bar waters. As the thermal bar moved offshore the spring phytoplankton bloom followed. This intense bloom used a considerable portion of the surface nutrient pool. As a result, the relationships between variables changed quickly during the late spring. Thermal stratification, which separates surface and deep waters, was more static in that large changes in correlations were not evident between summer cruises. In addition, Saginaw Bay water moved more readily across southern Lake Huron, so the factor analysis extracted just two factors by late summer -- hypolimnion and epilimnion. Cooling and mixing processes of the fall reduced the differences between surface and deep waters, and the correlations changed again.

CONCLUSION

Southern Lake Huron in 1974 was a system dominated by three limnological periods: homothermous, thermal bar, and thermally stratified. The transition between these periods was brief in 1974 while conditions during each period were noticeably different from the other two. Large shifts in the relationships of variables among one another marked the transition between two periods. These shifts were evident in the correlation and factor analyses. The results of the analysis for cruises 3 and 4 were quite different despite the fact that only two weeks separated the two.

Although homothermous conditions were never fully reestablished during the fall sampling, the correlations and factor analyses implied a return to winter conditions. The transition between stratified summer conditions and homothermous winter conditions did not occur as rapidly as the reverse process, the onset of spring thermal stratification. Nevertheless, the data analysis showed a large amount of change between the October and the November cruise.

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SECTION 5

EUCLIDEAN DISTANCES

by T. Dennis Berry

INTRODUCTION

Analysis of large data sets consisting of data from many stations and variables measured at each station is complicated by the presence of large spatial and temporal variations that can obscure general trends and make interpretation difficult. One of the roles of multivariate statistical techniques is to find unifying principles that help explain the observed variation.

Some statistical techniques (for example, multivariate analysis of variance, MANOVA) require a well-balanced database to be applicable. Such analyses applied to the southern Lake Huron data set would require a subset of observations so small that inferences about spatial and temporal variation would be impossible. The application of such techniques also requires several assumptions such as randomness, independence, and normality, which may not be justified in this instance. Because of these limitations, other methods of analysis were pursued.

It has long been recognized that graphical techniques in data analysis are a great aid in data interpretation. For example, a contour map of surface temperature is often easier to interpret than a table of numbers. However, the southern Lake Huron data set includes eight cruises with nineteen variables measured at a series of depths on each cruise from which a total of 152 contour maps could be prepared for surface samples alone. Even in graphical form, this is a lot of information to assimilate in a short time. In order to reduce the number of plots, I have integrated all the variables from each depth by calculating the euclidean distance in a multi-variable space between each station and a reference station. These distances were then contoured for each cruise at depths of 1 and 5 m, reducing the total number of plots from a maximum number of 304, if all variables were plotted individually, to only 16 plots of euclidean distance contours for these two depths.

METHODS

The method is based on the calculation of the euclidean distance between a given station and a reference station in multi-dimensional space. To illustrate the method it is assumed that two variables, temperature and specific conductance, have been measured and plotted as shown in Figure 5.1. Arbitrarily choosing point A (with coordinates Xa,Ya) as the reference, the

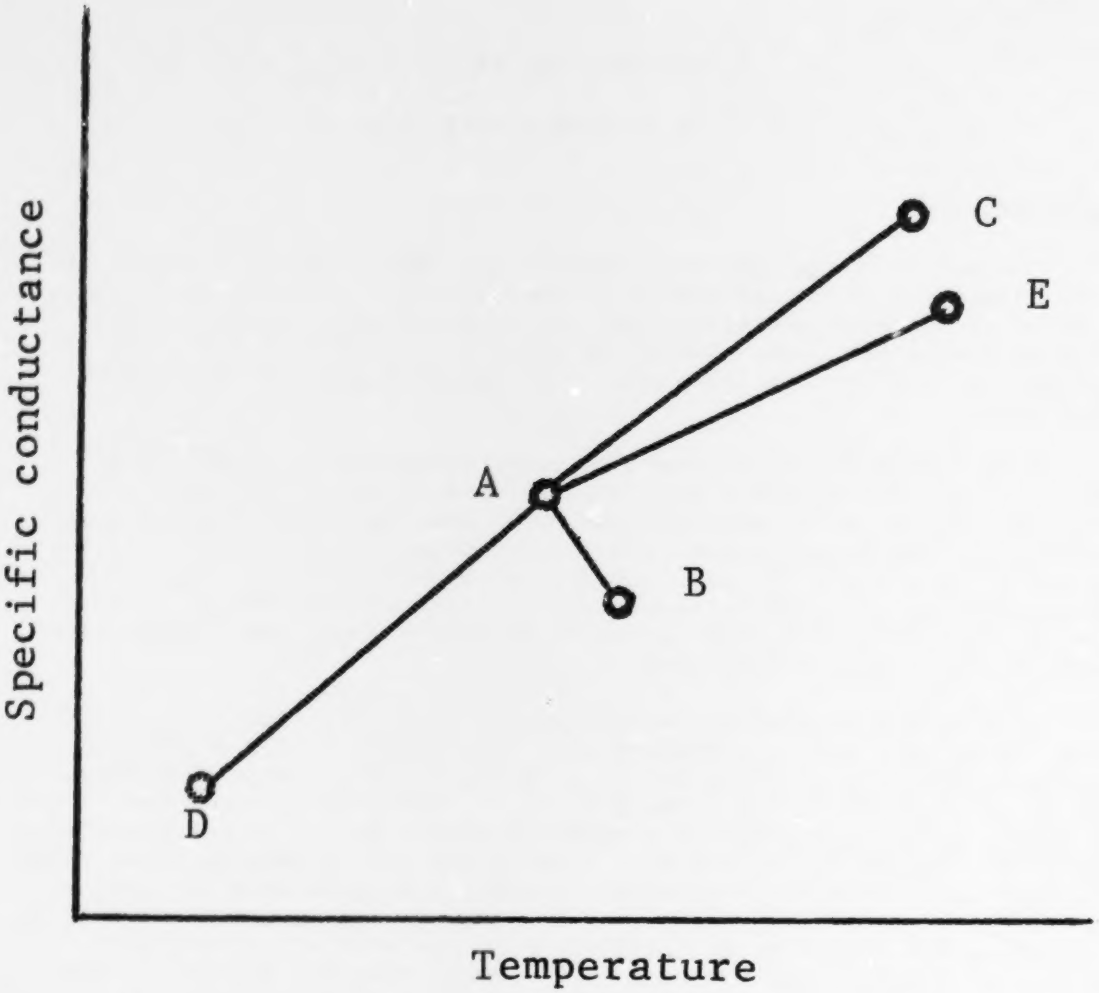
Specific conductance
Temperature
C
E
A
B
D

Figure 5.1. Example of stations plotted in arbitrary temperature and specific conductance coordinates.

euclidean distance between point A and any other point (with coordinates X,Y) can be calculated using the formula

$$\text{euclidean distance} = [(Xa - X)^2 + (Ya - Y)^2]^{1/2}.$$

From Figure 5.1 several things are evident. First, the smaller the euclidean distance, the more closely a given point resembles the reference for all variables measured. Second, two points such as C and D could have the same euclidean distance (from A) and be very different from each other. Points C and F, however, have the same euclidean distance (from A) and are closely related. The euclidean distance indicates only the degree of similarity between a given point and the reference, measured in arbitrary units, and gives little information about the relationship between points having the same euclidean distance. Therefore, as euclidean distance increases, the variability among points with the same distance has the potential to increase; but, points having small euclidean distances are all closely related to the reference and thus one another. Third, Figure 5.1 demonstrates that the magnitude of the euclidean distance calculated will depend on the choice of units used on the axis. In the calculations used for this analysis, each variable was normalized to a mean of zero and a standard deviation of one so that all variables would be weighted equally in the analysis.

The choice of a reference station is important because of its effect on the interpretation of the results. Since the greatest amount of information is obtained about stations that have a small euclidean distance from the reference, the reference station should be chosen in the area of prime interest. For the purposes of this analysis, a reference station (Table 5.1) characteristic of the open lake was chosen so that stations that were very different from the open lake would have large euclidean distances.

Euclidean distances were calculated for cruises 2 through 8 at depths of 1 m and 5 m. The stations and reference used varied as a result of missing data and are shown in Table 5.1. Twelve variables were used in the analysis: temperature, Secchi transparency, pH, soluble silica, particulate silica, nitrate, chloride, ammonia, total phosphorus, specific conductance, and sulfate. The only exception to this was cruise 6 which does not include nitrate data because of a large number of missing values for this variable.

Calculated euclidean distances were contoured using an interactive computer contouring program. The program superimposed a rectangular grid of points over the sampling area and calculated a euclidean distance for each of these points using a weighted (by distance) average of the six nearest stations. This grid was then contoured using the algorithm of Cottafava and LeMoli (1969).

RESULTS

The percentage of the observed variation explained by the contouring algorithm as shown in Table 5.2 was calculated by squaring the difference between the observed and predicted values, summing these, and dividing by N (the number of stations). Many of the contours fit the observed data poorly,

TABLE 5.1. STATIONS AND REFERENCE USED FOR THE 1 M PLOTS[1]

Station	Cruise						
	2	3	4	5	6	7	8
06	X	X	X		X	X	X
07	X	X	X		X	X	X
09	X	X	X	X	X		X
10	X	X	X		X	X	X
11	X	X	X		X	X	X
13			X	X	X	X	X
14	X	X	X	X	X	X	X
15		X	X	X	X	X	X
16	X	X	X	X	X	X	X
20	X	X		X	X		
21		X	X	X			
23	X	X	X	X	X	X	X
24	X	X	X	X	X	X	
25		X	X	X	X	X	X
26		X	X		X	X	X
36	X	X	X	X	X	X	X
37	X	X		X	X	X	X
38	X	X	X	X	X	X	X
39	X	X	X	X	X	X	X
40	X	X	X		X	X	X
41	X	X	X		X	X	X
42	X	X	X	X	X	X	X
43	X	X	X	X	X	X	X
44		X	X	X		X	X
45		X		X	X	X	X
46		X		X	X	X	X
47		X		X	X	X	X
48	X			X	X	X	
49	X	X	X	X	X		X
50	X	X		X	X		X
51	X	X	X		X	X	X
52	X	X	X	X	X	X	X
53	X	X	X	X			X
54		X	X	X	X	X	
55	X		X				X
56	X	X		X	X		X
57	X	X	X	X	X		X
58		X	X	X	X		X
60		*	*	*	*	*	
63	X	X	X			X	X
64	X	X	X		X	X	X
65	X	X	X		X	X	X
66	*	X				X	*
67	X	X	X	X	X	X	X

[1] X = stations used in analysis * = reference station

TABLE 5.2. DESCRIPTIVE STATISTICS FOR THE EUCLIDEAN DISTANCES BY CRUISE AND DEPTH

Cruise	Depth	N	%	Min.	Max.	Mean	Std. Dev.
2	1	30	42	0.345	3.469	1.060	0.687
2	5	29	40	0.403	3.289	1.067	0.677
3	1	40	51	0.415	3.039	1.202	0.555
3	5	38	31	0.476	3.083	1.187	0.548
4	1	34	69	0.675	3.481	1.368	0.665
4	5	36	72	0.641	3.453	1.361	0.650
5	1	30	53	0.642	2.149	1.280	0.321
5	5	33	51	0.711	2.530	1.286	0.374
6	1	43	33	0.496	3.491	1.201	0.567
6	5	47	33	0.651	3.840	1.431	0.543
7	1	34	73	0.456	2.487	1.047	0.438
7	5	36	72	0.369	2.822	1.168	0.520
8	1	42	61	0.377	2.834	1.068	0.504
8	5	41	41	0.659	2.772	1.280	0.409

Information tabulated is: number of stations included in the analysis, percentage of variation in the data explained by analyses, and the minimum, maximum, mean, and standard deviation of the euclidean distances.

explaining less than 50 percent of the variation. While these contours imply a synoptic picture of the lake, it took several days to collect the data. During this period, the conditions were not static, especially when the sampling was interrupted by bad weather. A major wind event, for example, could cause considerable mixing across existing gradients, move surface waters, and deepen the epilimnion (if the lake were stratified). It is obvious that any combination of these events would change the multivariate spatial relationships of the stations, both horizontally and with depth. This could result in anomalous stations with a concomitant decrease in the percentage of the variation explained by the contours.

Thermal Bar

The euclidean distance contours for the second cruise (Figure 5.2) showed a strong relationship to the thermal bar in both the 1 m and 5 m plots. In general the contours were oriented parallel to shore, but the gradient was more intense along the Canadian shore than along the U.S. shore. This implied two things: first, that water along the Canadian shore was in some respects more different from the open lake than water along the U.S. shore and second, that some factor other than temperature was causing the increased intensity of the gradient. This other factor was most likely nitrate, which had a strong gradient along the Canadian shore (see Sections 3 and 7).

Spring Warming

During this period, the plots were similar with gradients across the mouth of Saginaw Bay and parallel to the U.S. and Canadian shores (Figures 5.3 and 5.4). The euclidean distance contours tended to follow the depth contours indicating that differences in water quality were primarily the result of nearshore effects. Again, the gradients were more intense along the Canadian shore than along the U.S. shore. This pattern of isopleths corresponds with those observed for several physical-chemical variables (see Section 3).

Summer Stratification

The euclidean distance contours during this period showed gradients across the N-S axis of the lake (Figures 5.5 and 5.6) in contrast to the predominantly E-W gradients observed earlier in the year. This indicated a change in the relationship between the southern and northern basins of the lake. The contours from cruise 5 (Figure 5.5) were difficult to interpret because of the lack of data in the central portion of the southern basin.

The most interesting features of the summer cruise 6 euclidean distance contours (Figure 5.6) were the strong gradients along the north shore of Saginaw Bay and the close relationship (small euclidean distances) of the stations in the central part of the southern basin and stations near the south shore of Saginaw Bay.

During summer stratification, water circulation patterns in the epilimnion were dependent on weather (Sloss and Saylor, 1975). Light NNE winds prevailed during cruise 5, and the euclidean distance contours

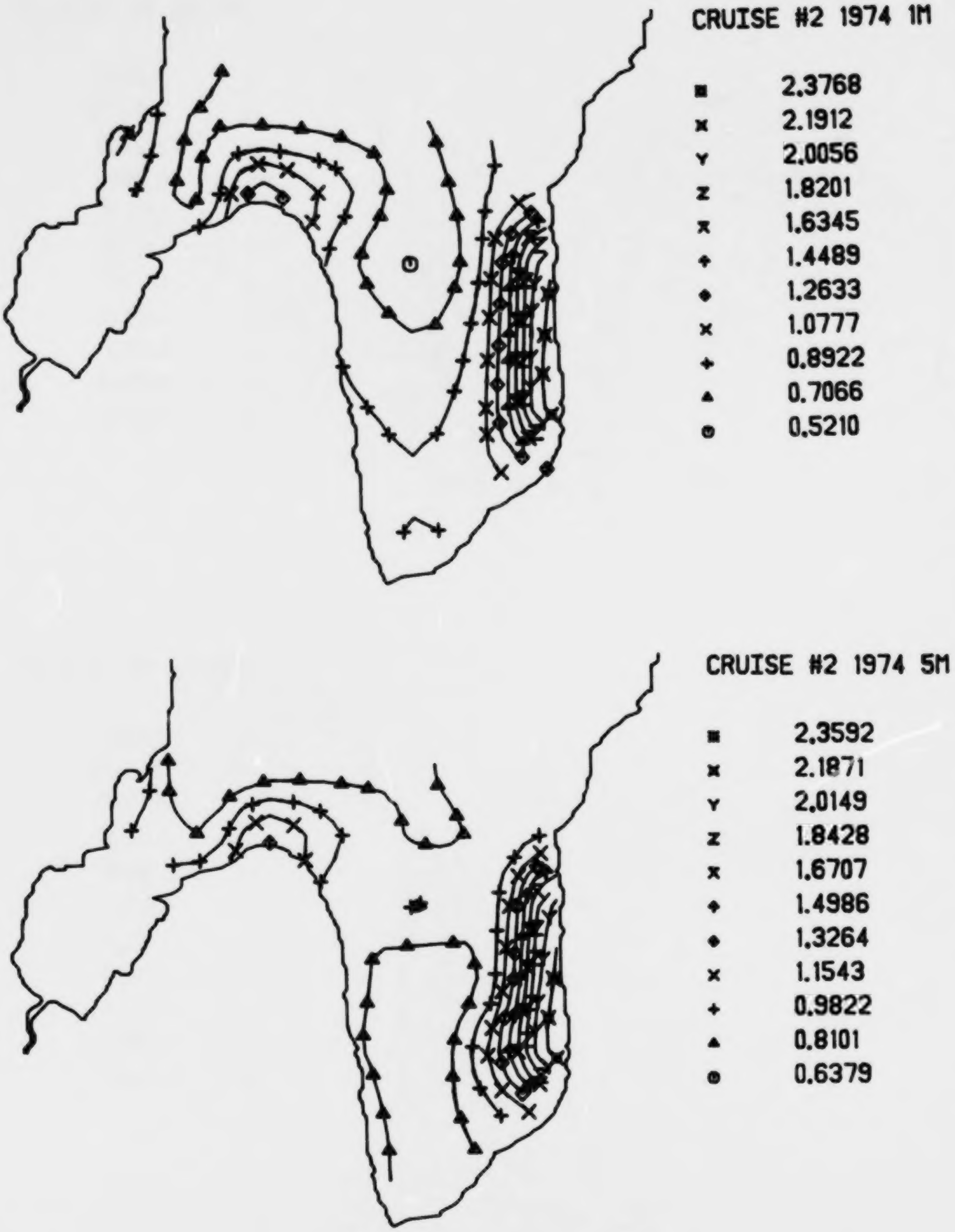
CRUISE #2 1974 1M
■ 2.3768
× 2.1912
Y 2.0056
Z 1.8201
× 1.6345
+ 1.4489
◆ 1.2633
× 1.0777
+ 0.8922
▲ 0.7066
⊙ 0.5210
CRUISE #2 1974 5M
■ 2.3592
× 2.1871
Y 2.0149
Z 1.8428
× 1.6707
+ 1.4986
◆ 1.3264
× 1.1543
+ 0.9822
▲ 0.8101
⊙ 0.6379

Figure 5.2. Contours of multivariate euclidean distances from the reference station. For Cruise 2.

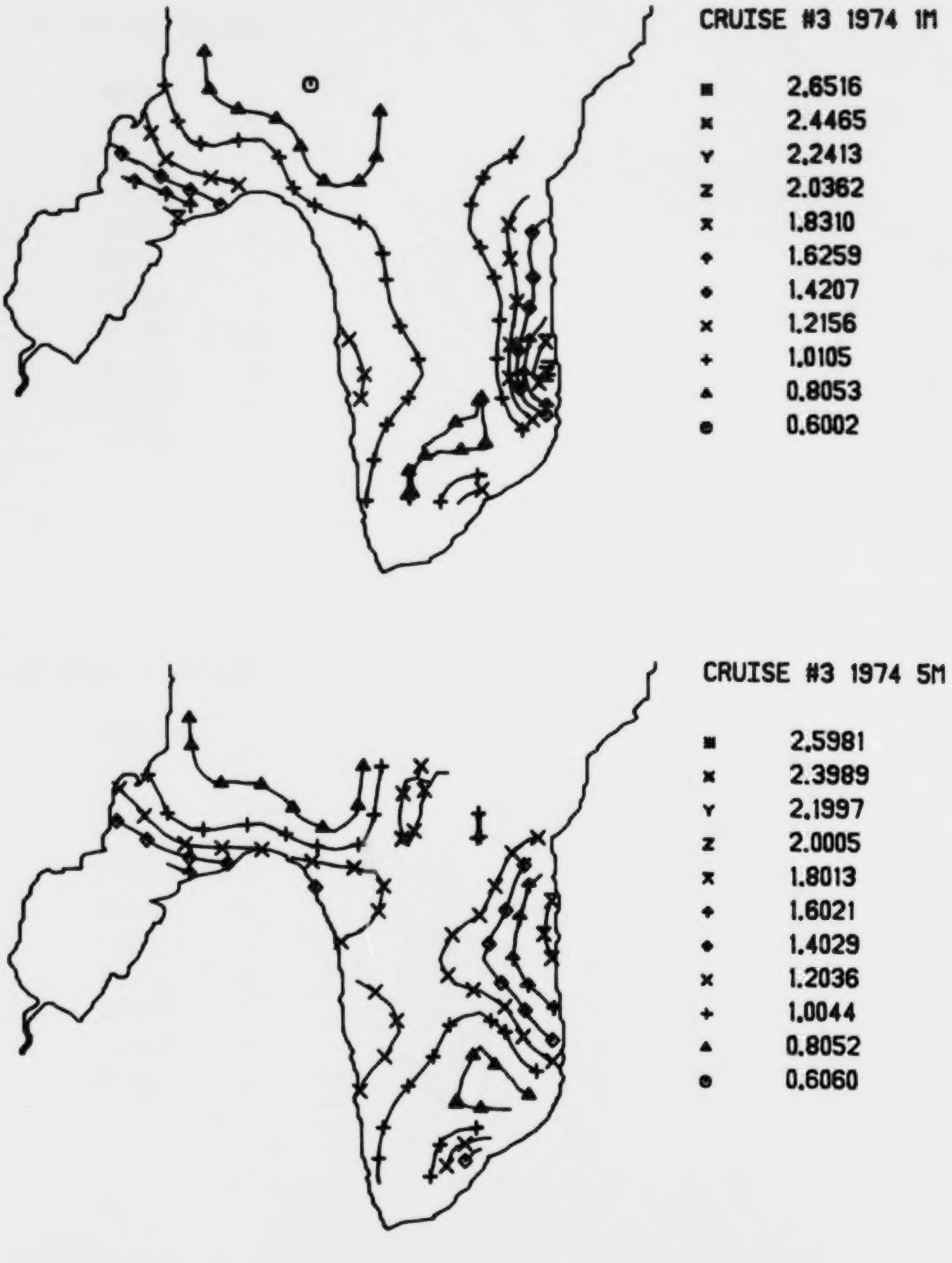
CRUISE #3 1974 1M
■ 2.6516
× 2.4465
Y 2.2413
Z 2.0362
× 1.8310
◆ 1.6259
● 1.4207
× 1.2156
+ 1.0105
▲ 0.8053
⊙ 0.6002
CRUISE #3 1974 5M
■ 2.5981
× 2.3989
Y 2.1997
Z 2.0005
× 1.8013
◆ 1.6021
● 1.4029
× 1.2036
+ 1.0044
▲ 0.8052
⊙ 0.6060

Figure 5.3. Contours of multivariate euclidean distances from the reference station. For Cruise 3.

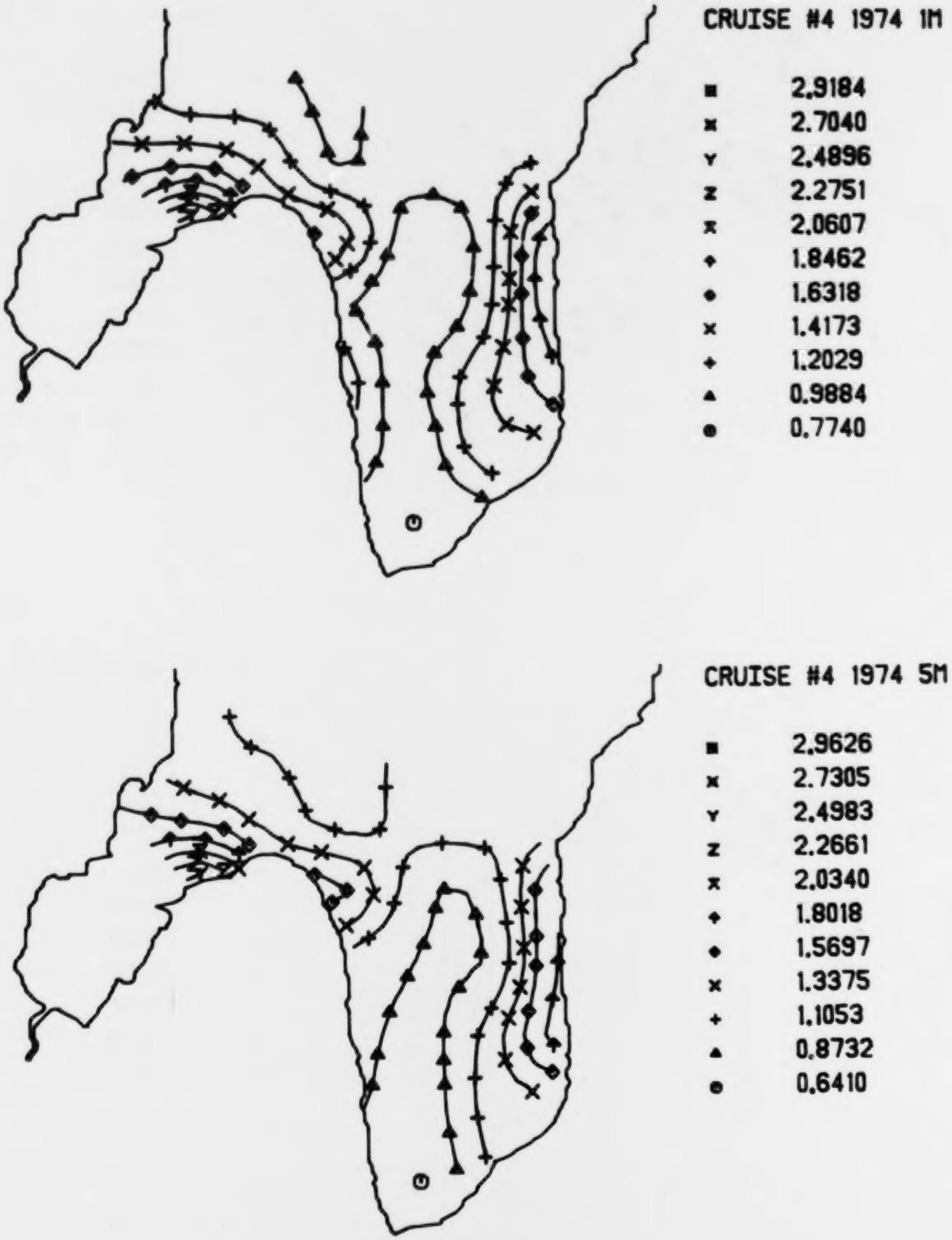
CRUISE #4 1974 1M
■ 2.9184
× 2.7040
Y 2.4896
Z 2.2751
× 2.0607
+ 1.8462
◆ 1.6318
× 1.4173
+ 1.2029
▲ 0.9884
● 0.7740
CRUISE #4 1974 5M
■ 2.9626
× 2.7305
Y 2.4983
Z 2.2661
× 2.0340
+ 1.8018
◆ 1.5697
× 1.3375
+ 1.1053
▲ 0.8732
● 0.6410

Figure 5.4. Contours of multivariate euclidean distances from the reference station. For Cruise 4.

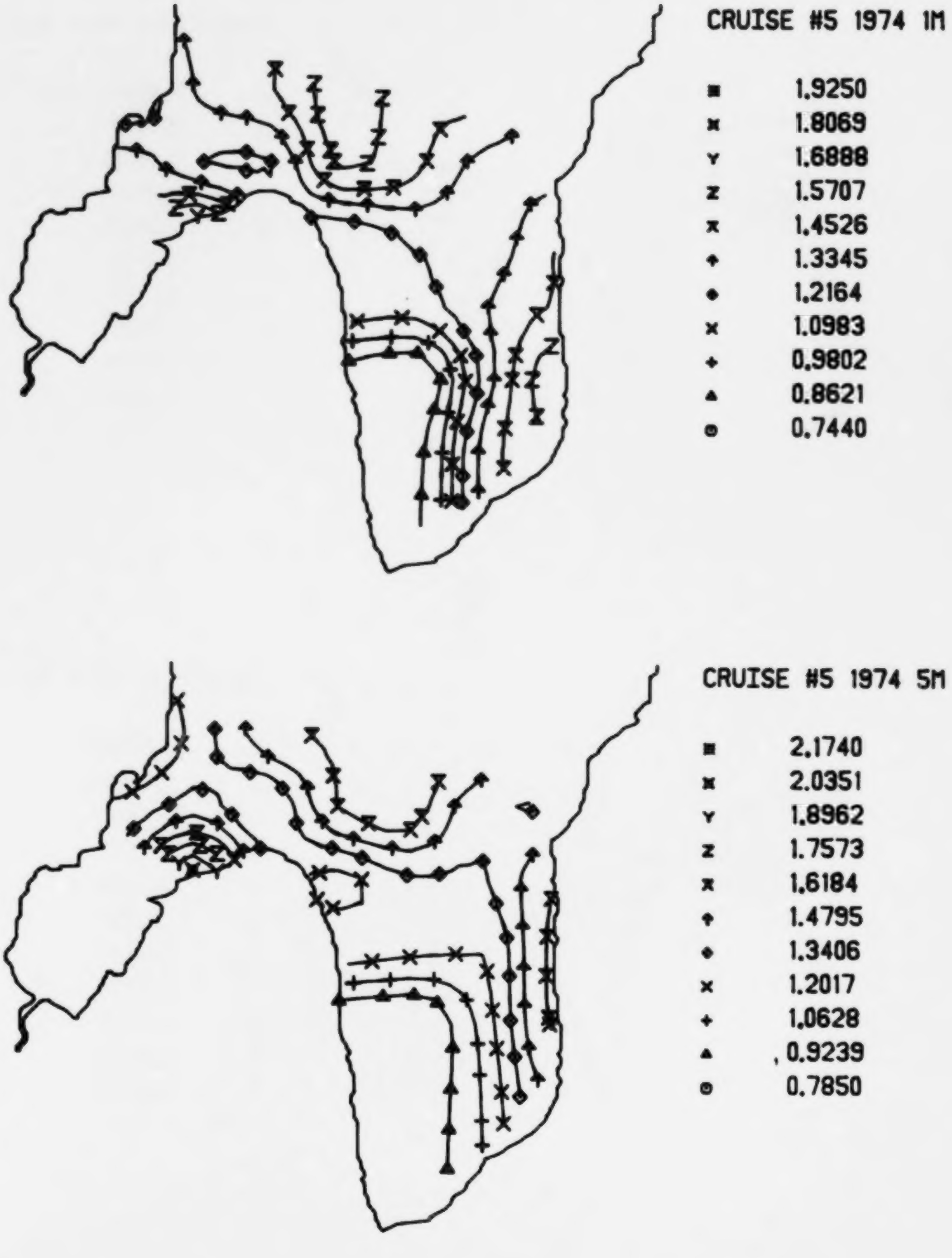
CRUISE #5 1974 1M
■ 1.9250
✱ 1.8069
Y 1.6888
Z 1.5707
X 1.4526
✦ 1.3345
◆ 1.2164
× 1.0983
+ 0.9802
▲ 0.8621
⊙ 0.7440
CRUISE #5 1974 5M
■ 2.1740
✱ 2.0351
Y 1.8962
Z 1.7573
X 1.6184
✦ 1.4795
◆ 1.3406
× 1.2017
+ 1.0628
▲ 0.9239
⊙ 0.7850

Figure 5.5. Contours of multivariate euclidean distances from the reference station. For Cruise 5.

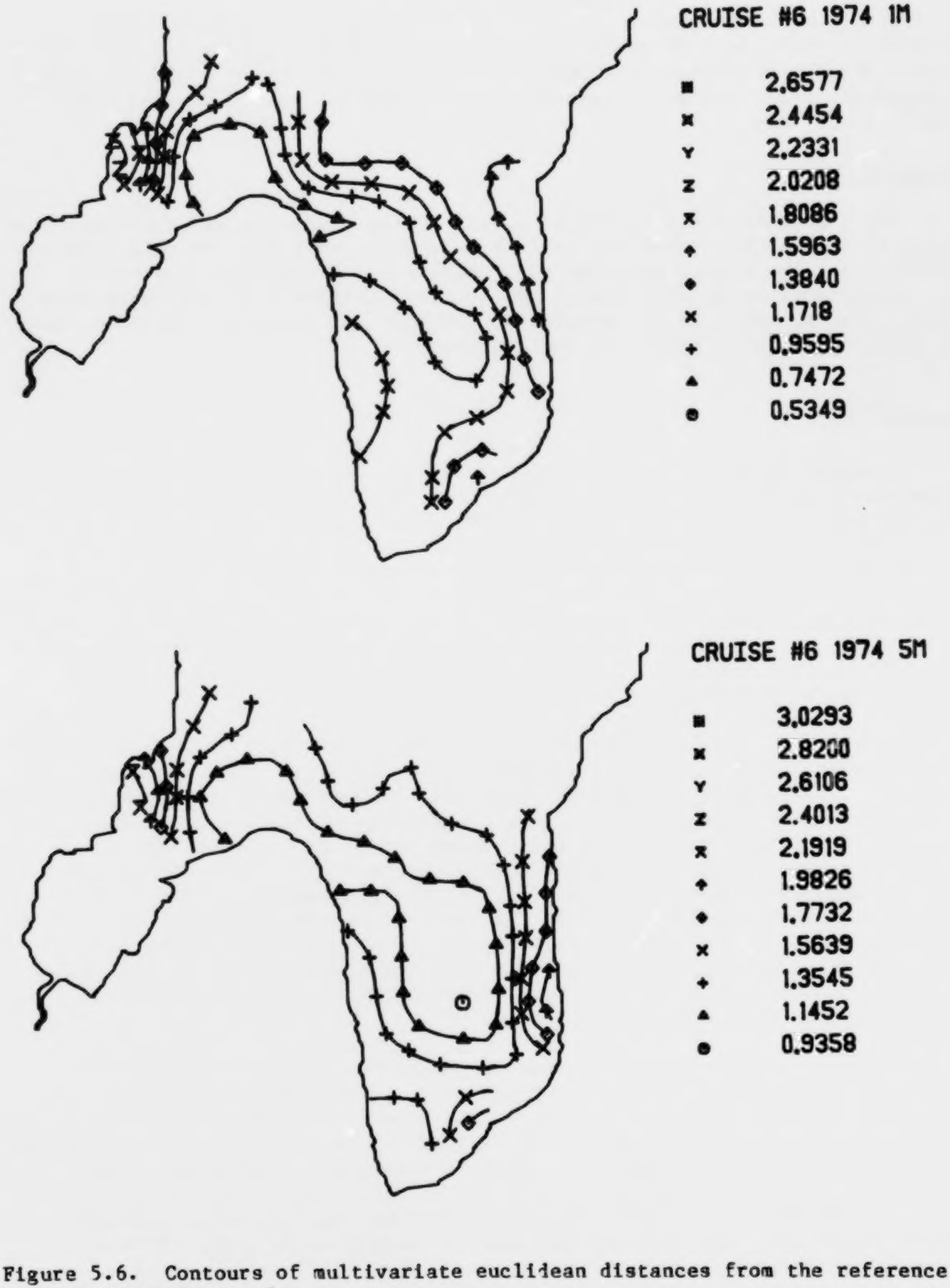
CRUISE #6 1974 1M
■ 2.6577
✖ 2.4454
Y 2.2331
Z 2.0208
✖ 1.8086
✦ 1.5963
◆ 1.3840
× 1.1718
+ 0.9595
▲ 0.7472
● 0.5349
CRUISE #6 1974 5M
■ 3.0293
✖ 2.8200
Y 2.6106
Z 2.4013
✖ 2.1919
✦ 1.9826
◆ 1.7732
× 1.5639
+ 1.3545
▲ 1.1452
● 0.9358

Figure 5.6. Contours of multivariate euclidean distances from the reference station. For Cruise 6.

indicated that water similar to open lake water was confined to the SW portion of the lake. SW winds were predominant before and during the sixth cruise and the euclidean distance contours for this cruise indicated that Saginaw Bay water had been transported north and was held along the north shore of the bay.

Autumnal Cooling

The 1 m plots for this period showed strong gradients along the southern shore of Saginaw Bay. For cruise 7 (Figure 5.7), this was the only gradient present over the entire sampling area which implied that the lake was horizontally mixed at this depth. On cruise 8 (Figure 5.8) gradients were present across the southern portion of the lake and along the Canadian shore in addition to the gradient in Saginaw Bay.

CONCLUSIONS

Contours obtained from the analysis of euclidean distances do not give a water quality value to a given point in the lake, but general patterns of changes in water quality or water mass movement can be traced with the contours. The area at the mouth of Saginaw Bay illustrates this point. During periods of SW winds, bay water was situated along the north shore of the bay as shown in the plots from cruise 6. During periods of northerly winds, bay water was found along the southern shore of Saginaw Bay as the plots from cruise 5 show. In these plots, the general water mass patterns are evident, but the water quality at any given station at the mouth of Saginaw Bay is probably not predicted by the contours.

Contours of euclidean distances show water mass distribution as areas of water quality in relation to differences from open lake water quality. Information concerning the prevailing winds, combined with the contour maps, imply water mass movement. The first two cruises produced maps dominated by the thermal bar conditions. An interesting aspect of contours from these cruises is the similarity of gradients along the Ontario shore of Lake Huron and the mouth of Saginaw Bay. Apparently, the high nutrient runoff from Ontario farms in the spring alters the open lake water quality as much as the highly eutrophic water leaving Saginaw Bay. The thermal bar keeps the enriched water near the Canadian shore allowing phytoplankton blooms to develop. A comparable high nutrient situation did not develop along the U.S. shore south of Saginaw Bay.

Because current patterns and water movements in Lake Huron were influenced by winds, a consistent water mass pattern was not observed. East-west contours as well as north-south contours were present during stratified conditions. Transport of Saginaw Bay to the open lake was subject to the prevailing winds, and the resulting widely fluctuating water mass distributions indicate the problem of determining boundaries for the segmentation of the lake into regions of similar water quality. Certain parts of the lake tend to have consistently oligotrophic (open northern waters) or eutrophic waters (inner Saginaw Bay), but in other areas, differing wind regimes readily shift epilimnetic waters about, complicating segmentation of the lake into areas of uniform water quality.

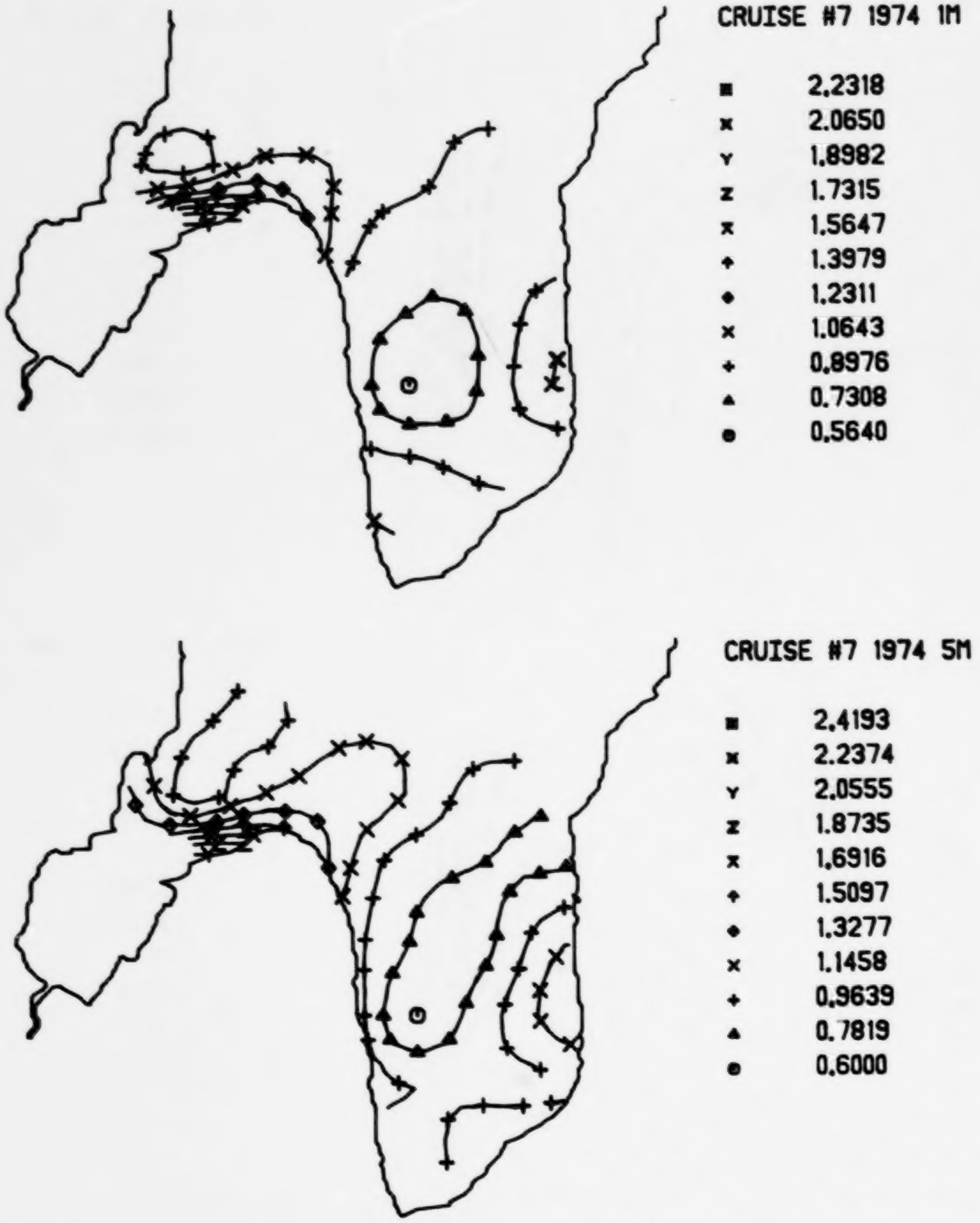
CRUISE #7 1974 1M
■ 2.2318
x 2.0650
Y 1.8982
Z 1.7315
x 1.5647
+ 1.3979
◆ 1.2311
x 1.0643
+ 0.8976
▲ 0.7308
● 0.5640
CRUISE #7 1974 5M
■ 2.4193
x 2.2374
Y 2.0555
Z 1.8735
x 1.6916
+ 1.5097
◆ 1.3277
x 1.1458
+ 0.9639
▲ 0.7819
● 0.6000

Figure 5.7. Contours of multivariate euclidean distances from the reference station. For Cruise 7.

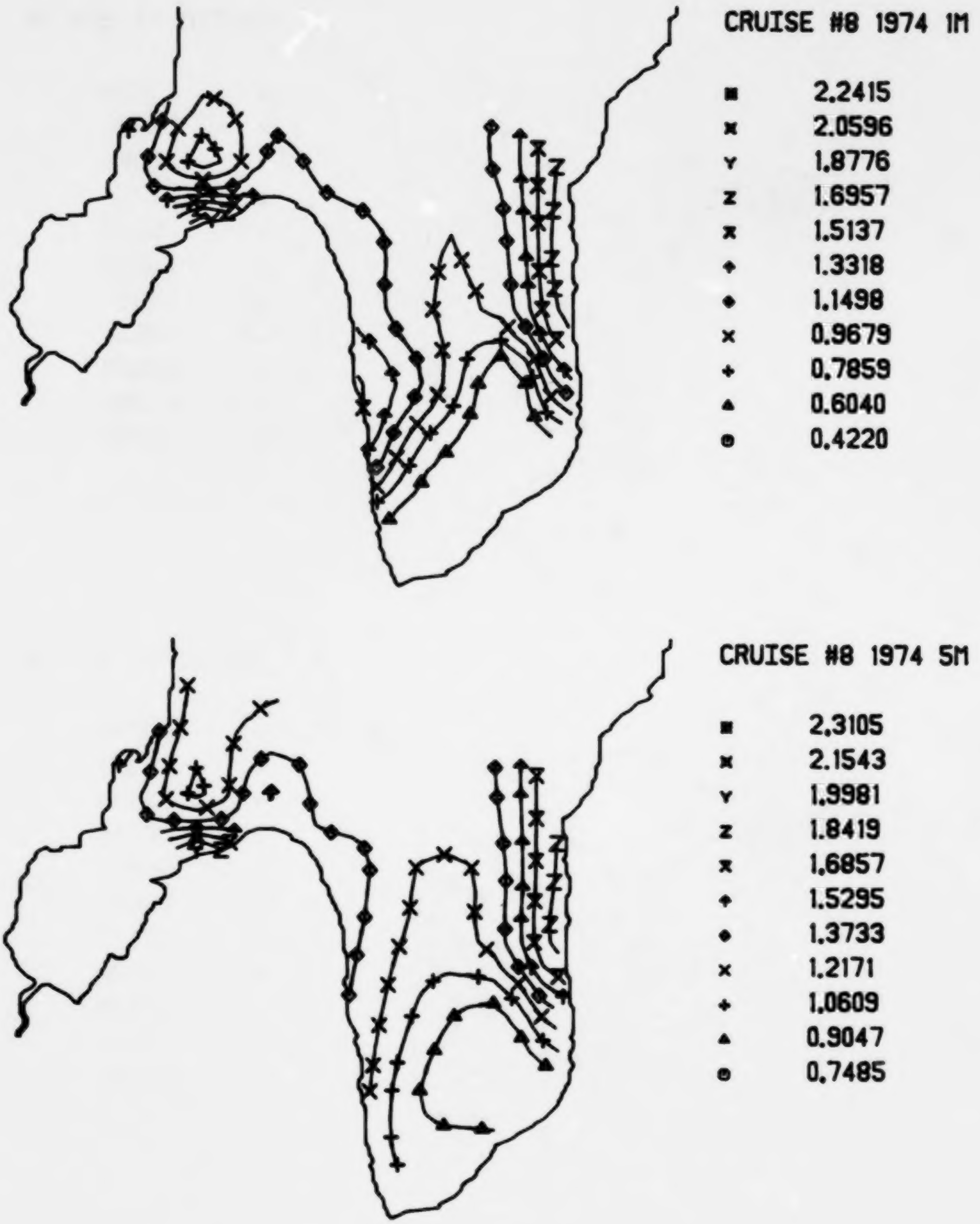
CRUISE #8 1974 1M
■ 2.2415
✱ 2.0596
Y 1.8776
Z 1.6957
X 1.5137
✚ 1.3318
◆ 1.1498
× 0.9679
+ 0.7859
▲ 0.6040
● 0.4220
CRUISE #8 1974 5M
■ 2.3105
✱ 2.1543
Y 1.9981
Z 1.8419
X 1.6857
✚ 1.5295
◆ 1.3733
× 1.2171
+ 1.0609
▲ 0.9047
● 0.7485

Figure 5.8. Contours of multivariate euclidean distances from the reference station. For Cruise 8.

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SECTION 6

PHYTOPLANKTON DYNAMICS IN OUTER SAGINAW BAY

by Russell A. Moll

The Laurentian Great Lakes have been closely watched in recent years by both the U. S. and Canadian governments for changes in water quality. Emphasis has been placed on monitoring the lakes and using the data collected in preditive models (Thomann et al., 1976; Bierman and Dolan, 1976). However, research efforts have been stifled by the lack of data in certain aspects of limnology, primarily rates of biological processes. There are relatively few places to study phytoplankton in the Great Lakes where point sources of pollution move into relatively clear water. In these areas, the high concentration of nutrients and organisms provide ample material for study while allowing insight as to how the open lake will react to future nutrient loadings. Areas of the upper Great Lakes suitable for this type of study include plumes of rivers in Lake Michigan, the mouths of Green and Saginaw Bays, and a few single point pollution sources in Lake Superior (International Joint Commission, 1976).

During 1975, studies were conducted in the mouth of Saginaw Bay, an area where oligotrophic open lake water mixes with eutrophic bay water (Sections 2 and 3). Four research cruises were conducted between early May and October. Water quality regions were identified before and after each cruise so that experiments could be conducted in eutrophic bay water, oligotrophic lake water, and as close to the interface of the two as possible. Different water masses were identified by underway sampling conducted in the mouth of the bay. Once the zones of water quality were located, a series of biological, chemical, and physical measurements were repeated in each area.

The sampling area was confined to the proximity of the front between bay and open lake water which was normally between two lines of stations in the mouth of the bay (stations 36-40 and 41-45) (Figure 6.1). The water in this area was deep enough to allow thermocline development throughout most of the summer. The study was restricted to an area which could be sampled by underway techniques in 6-8 hrs.

METHODS

Four cruises were conducted in the mouth of Saginaw Bay in 1975: 5-9 May, 28 May to 1 June, 31 July to 5 August, and 14-20 October. These cruises were designed to sample four different parts of the thermal cycle: early spring homothermous, early stratified, summer stratified, and fall homothermous.

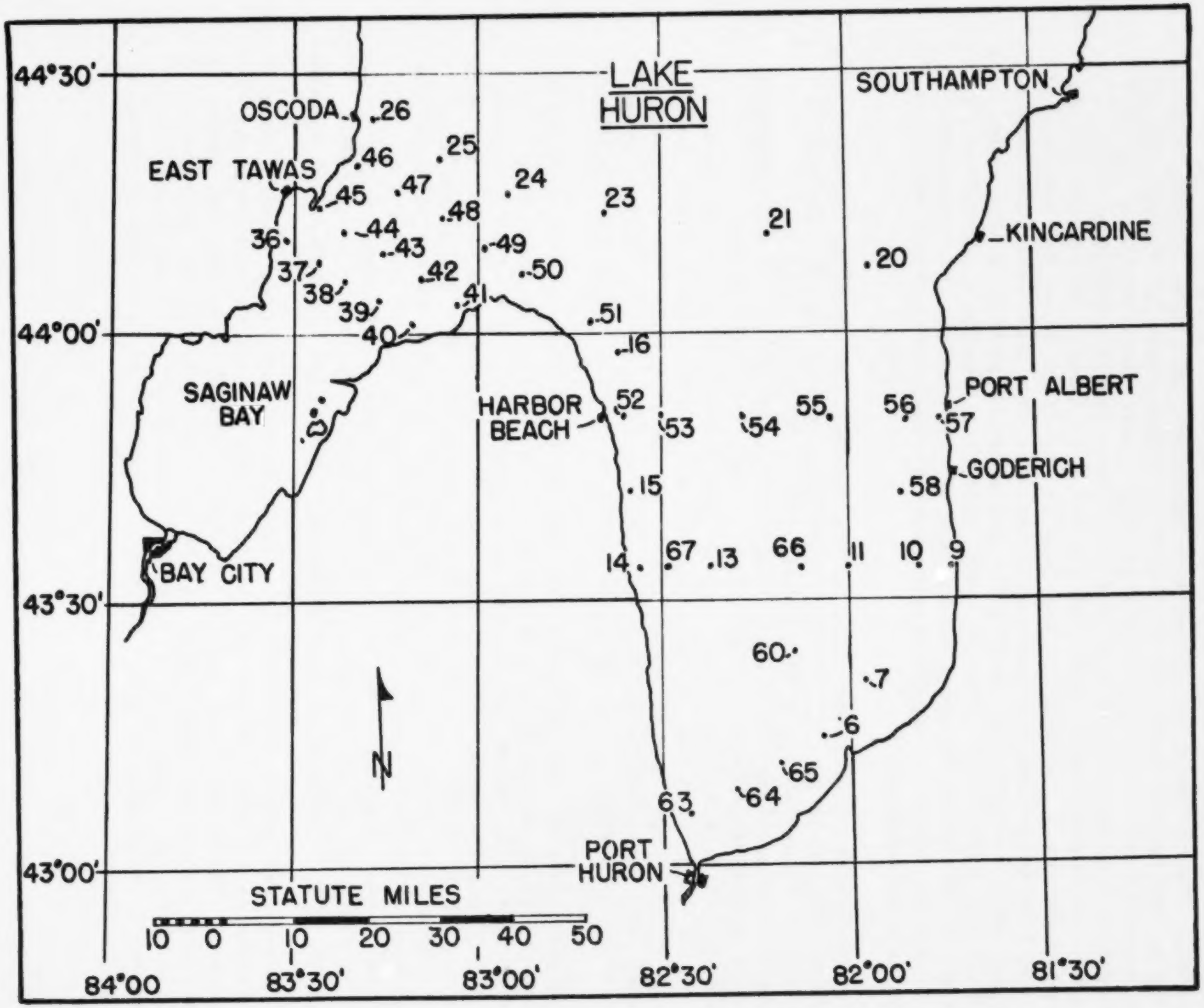

LAKE HURON
SOUTHAMPTON
KINCARDINE
PORT ALBERT
GODERICH
OSCODA
EAST TAWAS
SAGINAW BAY
BAY CITY
HARBOR BEACH
PORT HURON
STATUTE MILES
10 0 10 20 30 40 50
N
44°30'
44°00'
43°30'
43°00'
84°00
83°30'
83°00'
82°30'
82°00'
81°30'
26
25
46
47
24
45
23
48
21
44
36
43
49
20
37
42
50
38
41
39
51
40
16
52
53
54
55
56
57
58
15
14
67
13
66
11
10
9
60
7
6
65
63
64

Figure 6.1. Area sampled (between stations 36-40 and 41-45) during study of Saginaw Bay, 1975.

Initial sampling of each cruise consisted of underway sampling or mapping. This sampling required drawing water from the ship's sea chest (about 1 m below the surface) and running a series of analyses while underway. The following variables were measured: chloride, silica, nitrate nitrogen, and ammonia nitrogen (all with an Autoanalyzer II system), in vivo fluorescence, and temperature. The in vivo fluorescence estimated in vivo chlorophyll a levels and is referred to as chlorophyll throughout this Section. A complete description of the underway mapping techniques can be found in Section 7. A decision was made in the field as to the location of bay and lake water from the underway data. The data were later fed into a computer with navigational information and plots of gradients were made. The gradient plots were made with the same contouring program as described in Section 5. The underway sampling program was repeated at the termination of our cruise to learn the extent of movement of the nutrient front during the three days of sampling.

Identification of water types in the bay mouth allowed the location of a sampling station in each water type. Sampling at each station included a bottle cast followed by a 4-hr incubation for ^{14}C uptake both for phytoplankton and bacteria. The ^{14}C uptake for phytoplankton was conducted in situ following the methods described in Hall and Moll (1975). Phytoplankton were incubated for 4 hr at the depth from which they were collected; incubation depths ranged from 1 m to 1% of surface light level. Uptake of ^{14}C by phytoplankton was corrected for dissolved loss and dark uptake. All light bottle incubations were run in duplicate. During rough weather in October, two sets of incubations were run in an on-deck incubator.

Measurement of bacterial activity followed the technique of Wright and Hobbie (1965) as modified by Herbland and Bois (1974). Bacteria were incubated for 4 hr using ^{14}C glucose as a substrate in 0.45×10^{-5} to 0.36×10^{-4} g/l concentrations. The technique of Herbland and Bois (1974) includes a correction in uptake of substrate for respired loss during incubation. Incubations were carried out in a dark on-deck incubator cooled with running lake water. Incubation temperatures were kept as close to collection temperatures as possible. One heterotrophic uptake series was run per station which served as an indication of bacterial affinity for glucose. Bacterial and phytoplankton incubations were made from the same water samples.

Along with samples collected for incubations, additional sample water was collected for the measurements of chemical, biological, and physical variables. These variables included temperature, pH, conductivity, total alkalinity, corrected chlorophyll a, chloride, silica, nitrate nitrogen, ammonia nitrogen, soluble phosphorus, and total PO_4-P. In addition, measurements were made at each station for Secchi disc transparency, surface sunlight intensity, and submarine downwelling light.

RESULTS

Underway Sampling

Results from the underway sampling or mapping yielded data that was used to locate broad fronts of changing water quality, determine the range of each variable measured in the study area, and locate sampling sites. Comparing maps from the beginning and end of each cruise provided some insight into the movement of bay and lake water during the cruise. Results of the underway sampling did not yield detailed maps of variable distribution or information about the vertical distribution of variables. Although six variables (temperature, chlorophyll, nitrate nitrogen, ammonia nitrogen, chloride, and silica) were measured for each map of the bay mouth, many variables showed only a small range and could not be used to distinguish between bay and lake waters.

The primary objective of the underway mapping was the location of the broad nutrient front in Saginaw Bay. Although this objective was achieved, the maps may suffer from having short-term applicability. Our results show that rapid, large-scale movements of water masses in the mouth of Saginaw Bay require several days. The water quality at the bay station (Station 38) did not change dramatically between two visits to this station within 48 hr. On the other hand, repeated visits to one station over a 7-day period did show large changes in chlorophyll a distribution and concentration (Figure 6.2).

Early May Cruise

Maps from the first cruise of 6 May produced contours (Figure 6.3) parallel to the mouth of the bay (NW to SE) indicating a broad front between open lake water and Saginaw Bay water. Contour lines were evenly spaced, implying a smooth gradient of variables in the mouth of the bay. Underway sampling on 8 May showed a small change in the surface distribution of variables from the 6th of May; Figure 6.4 shows that high silica and chloride water had moved closer to the southern shore of the bay near Hat Point.

Early May 1975 was a period dominated by thermal bar conditions. Saginaw Bay water was primarily inside the bar, while the open lake station was still homothermous. Table 6.1, which gives means and other statistics of the first cruise, showed May was a period of cold water (4.9°), moderate chlorophyll a levels ($1.86\ \mu g/l$), moderate silica levels (0.55 mg SiO_2/l), high ^{14}C uptake ($10.7\ \mu gC/l/h$), and assimilation ratio (5.04). Simple product-moment correlation coefficients were calculated between all variables (Table 6.2). Although many of the correlations were high ($> \pm 0.70$), as with the early cruises in 1974 (Section 3), a basic pattern was evident. The warmer waters behind the thermal bar were also the more productive waters (correlation between *in situ* uptake and temperature was +0.86). Silica was already low in these warm waters (temperature to silica correlation, -0.75) and likewise low in areas of high ^{14}C uptake (^{14}C to silica, -0.84). Bacterial activity was highly correlated with bay water (high correlation to temperature, chloride, and conductivity), but these correlations were based on a small sample size of four. Although there were additional high correlations most of these were either routine (as chloride to conductivity) or based on small sample sizes ($n < 6$).

The early May ^{14}C uptake profiles, obtained by *in situ* incubations in the bay, showed a high level of uptake from the surface to the bottom (Figure 6.5). Likewise, chlorophyll a biomass was distributed evenly throughout the

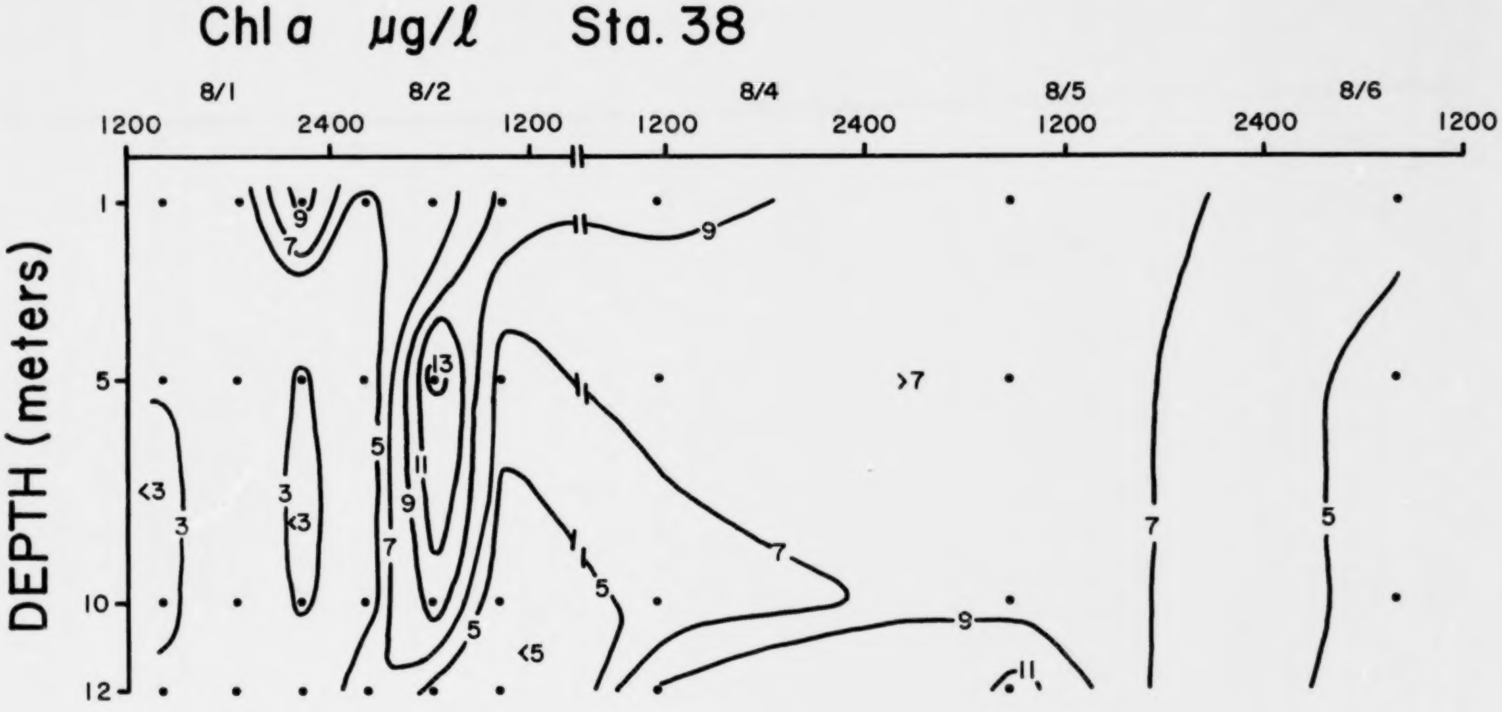
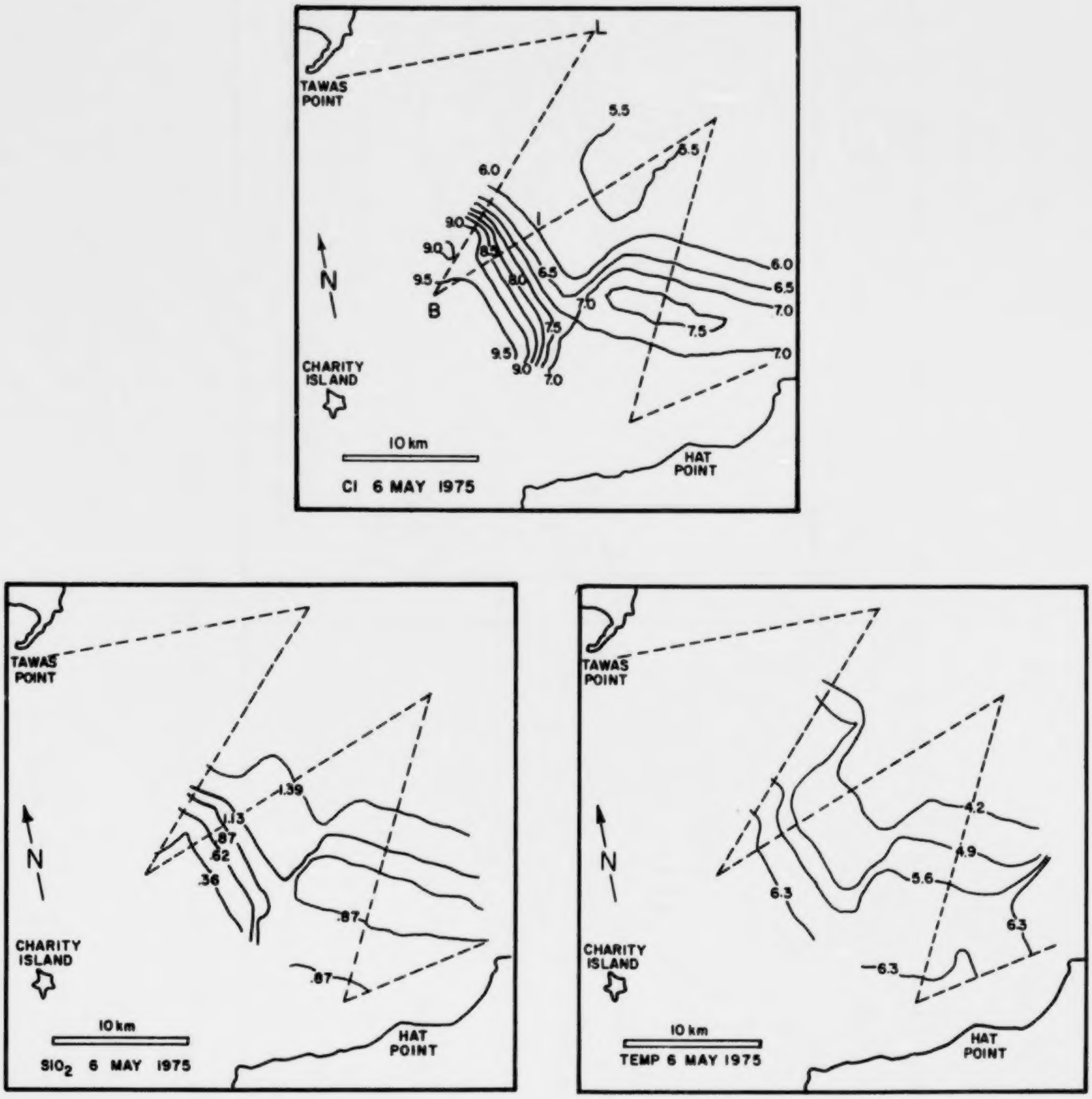


Figure 6.2. Vertical distribution of chlorophyll at station 38 from 4-6 August, 1975.


TAWAS POINT
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I
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7.5
7.5
9.5
9.0
7.0
7.0
N
CHARITY ISLAND
10 km
Cl 6 MAY 1975
HAT POINT
1.39
1.13
.87
.62
.36
.87
.87
SIO$_2$ 6 MAY 1975
4.2
4.9
5.6
6.3
6.3
6.3
TEMP 6 MAY 1975

Figure 6.3. Contour maps from cruise 1 of 1975 study (6 May).

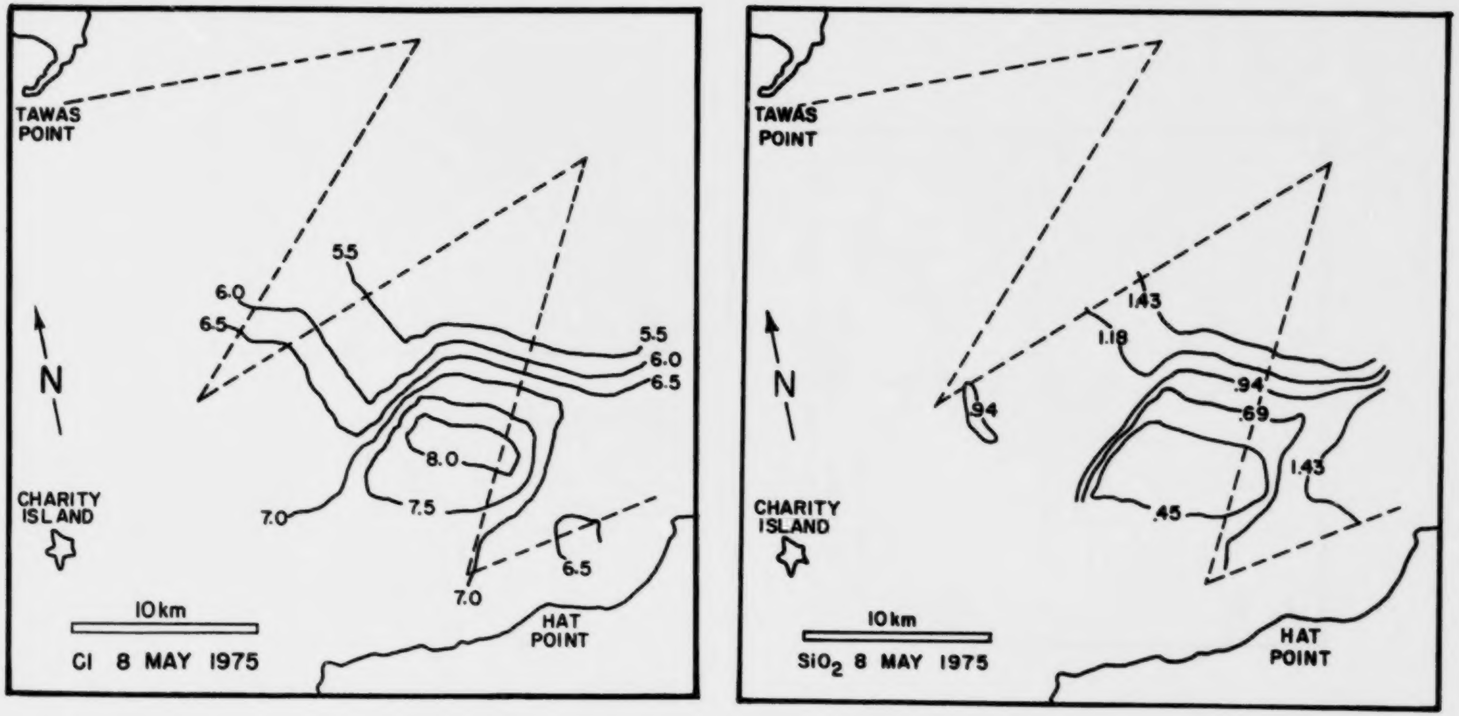

TAWAS POINT
CHARITY ISLAND
HAT POINT
N
10km
Cl 8 MAY 1975
5.5
6.0
6.5
7.0
7.5
8.0
SiO2 8 MAY 1975
1.43
1.18
.94
.69
.45

Figure 6.4. Contour maps from cruise 1 of 1975 study (8 May).

TABLE 6.1. DESCRIPTIVE MEASURES CRUISE #1 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	25	1.00	40.00	8.760	
Secchi	22	4.50	9.000	6.872	2.09
Water Temp	25	3.10	7.100	4.960	1.62
pH	25	8.31	8.600	8.453	.085
Chlorophyll a	24	.740	4.390	1.865	.948
Silica	25	.110	1.100	.5486	.313
Nitrate	25	180.7	368.2	280.3	35.48
Ammonia	25	3.80	21.84	11.68	4.33
Total Phosphorus	25	3.06	21.59	9.745	5.02
Total Soluble Phosphorus	25	2.02	12.09	4.668	2.38
Conductivity	25	1.82	2.481	2.273	.146
Alkalinity	18	19.13	23.45	21.30	1.35
Chloride	25	2.46	11.35	6.706	1.98
Primary Production	32	1.48	27.80	10.70	7.75
Assimilation Ratio	15	1.36	14.13	5.038	3.55
V_{max}	4	.040	3.961	1.377	1.76
Surface Light	22	69.5	940.0	669.2	303.3
Extinction Coefficient	22	.110	.3901	.2495	.076
Underwater Light	22	.040	574.0	125.4	170.4

TABLE 6.2. PRODUCT-MOMENT CORRELATIONS AMONG VARIABLES FROM CRUISE 1, 1975, SOUTHERN LAKE HURON

VARIABLE	DEP	SEC	TEMP	PH	CHL	SIO2	NO3	NH3	TPO4	SPO4	CL	VMAX	EXT	SUBL	C14
DEPTH	1.000														
SECCHI	.171 (22)	1.000													
H2O TEMP	-.237 (25)	-.987 (22)	1.000												
PH	-.447 (25)	-.756 (22)	.639 (25)	1.000											
CHL A	-.072 (24)	-.687 (21)	.588 (24)	.446 (24)	1.000										
SIO2	.276 (25)	.777 (22)	-.748 (25)	-.639 (25)	-.594 (24)	1.000									
NO3 N	.163 (25)	.005 (22)	.112 (25)	-.044 (25)	-.166 (24)	.283 (25)	1.000								
NH3 N	-.191 (25)	-.398 (22)	.408 (25)	.189 (25)	.204 (24)	-.626 (25)	-.293 (25)	1.000							
T PO4	-.062 (25)	-.529 (22)	.403 (25)	.364 (25)	.359 (24)	-.381 (25)	.143 (25)	.477 (25)	1.000						
S PO4	-.215 (25)	-.172 (22)	.110 (25)	.322 (25)	.062 (24)	-.148 (25)	-.222 (25)	.125 (25)	-.039 (25)	1.000					
CL	-.047 (25)	-.889 (22)	.827 (25)	.731 (25)	.501 (24)	-.634 (25)	.329 (25)	.302 (25)	.515 (25)	.105 (25)	1.000				
V MAX	-0. (4)	-.656 (4)	.780 (4)	.925 (4)	.246 (4)	-.872 (4)	-.637 (4)	.840 (4)	-.046 (4)	.851 (4)	.849 (4)	1.000			
EXT COEF	-.522 (22)	-.466 (22)	.510 (22)	.468 (22)	.452 (21)	-.541 (22)	-.329 (22)	.534 (22)	.383 (22)	.247 (22)	.241 (22)	.941 (4)	1.000		
SUBLITE	-.569 (22)	.023 (22)	.033 (22)	.323 (22)	-.087 (21)	-.165 (22)	-.103 (22)	-.039 (22)	-.190 (22)	-.145 (22)	-.048 (22)	.034 (4)	.225 (22)	1.000	
C14	-.226 (16)	-.834 (16)	.658 (16)	.706 (16)	.546 (15)	-.834 (16)	-.316 (16)	.401 (16)	.298 (16)	.033 (16)	.699 (16)	.890 (4)	.317 (16)	.003 (16)	1.000

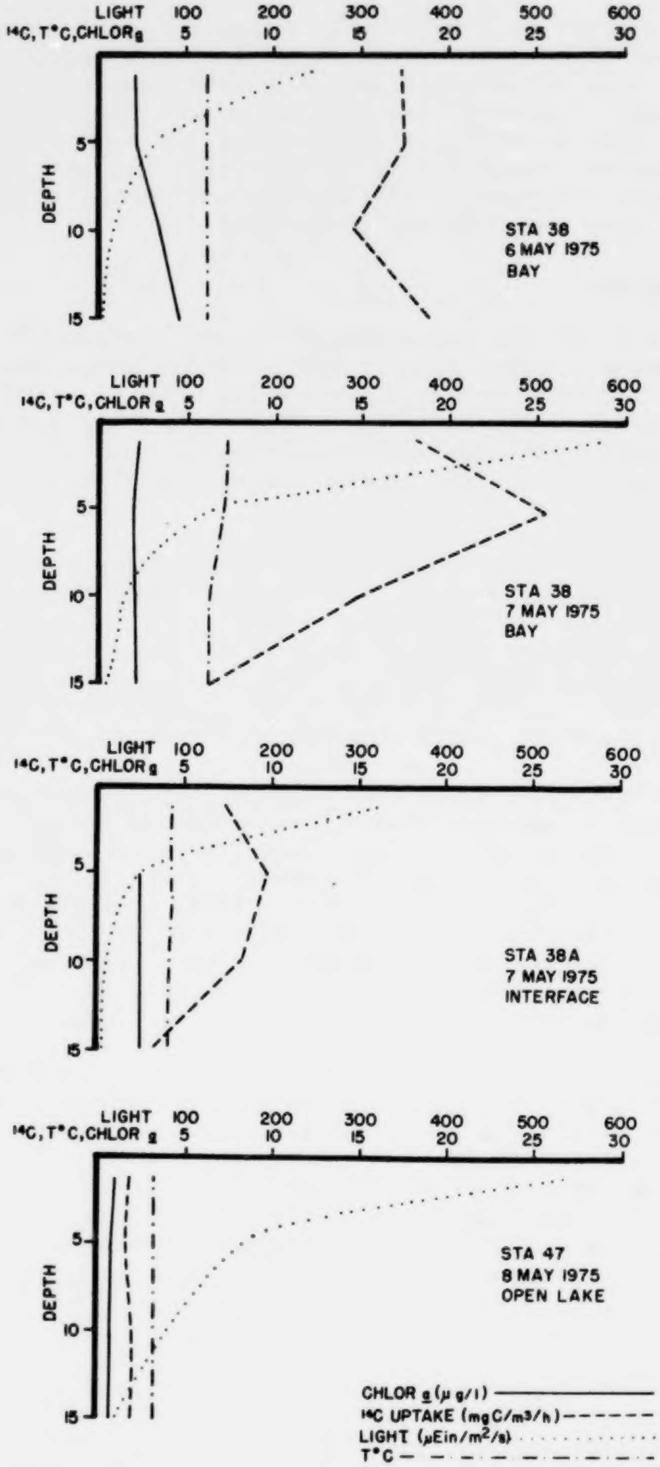


Figure 6.5. Results of the early May ^{14}C uptake profiles.

water column, and the assimilation ratios were high (from 3 to 14). The samples from the interface zone showed a similar amount of biomass but lower ^{14}C uptake than bay water (Figure 6.5) even though nutrients in this area were at higher concentrations than bay water. Bacterial activity was moderately high at both the interface and bay stations (Table 6.3). The open lake incubations revealed a small, but productive phytoplankton crop with a uniform depth distribution (Figure 6.5). Bacterial activity was low in early May at the open lake location (Table 6.3).

Late May Cruise

The underway sampling conducted on the first day of the second cruise, 29 May, showed a tongue of open lake water extending into Saginaw Bay toward Charity Island (Figure 6.6). Saginaw Bay water was confined primarily to the nearshore areas of the outer bay. Winds were light during the second cruise, and one result of the low wind velocities was very little change in the surface water distribution between the maps of 29 May and 1 June (Figures 6.6 and 6.7).

The transition between thermal bar conditions and stratified conditions was made between the early and late May cruises. Water temperatures warmed considerably from early to late May (increased to 11.7°), chlorophyll a biomass increased to 2.76 µg/l, but ^{14}C uptake, the assimilation ratio, and silica all decreased to 9.36 µgC/l/hr, 2.81, and .55 mg/l respectively. Table 6.4 shows that all nutrient concentrations were lower in late May than earlier in the month, except ammonia which increased.

The correlations among variables for the late May cruise also reflected the reduction of nutrient levels, a consequence of phytoplankton growth and vertical thermal stratification. Large negative correlations were found between nitrogen (as nitrate and ammonia), silica, and ^{14}C uptake (Table 6.5); these correlations should not be taken to imply cause and effect in terms of nutrient limitation, but that silica, nitrate, and ammonia were found at low levels when ^{14}C uptake was high. High positive correlations were found between ^{14}C uptake and phosphorus as total phosphorus and total soluble phosphorus.

Chlorophyll a biomass increased between the first two cruises in early and late May, yet ^{14}C uptake was lower in bay water yielding a lower assimilation ratio (Figure 6.8). Bacterial activity was also lower in late May than early May (Table 6.3). Chlorophyll a concentrations increased at the open lake station as did ^{14}C uptake; the assimilation ratio did not change for the open lake station between the two cruises. The biomass and ^{14}C uptake values were slightly lower for the interface station in late May. Bacterial activity was very high at the interface station.

August Cruise

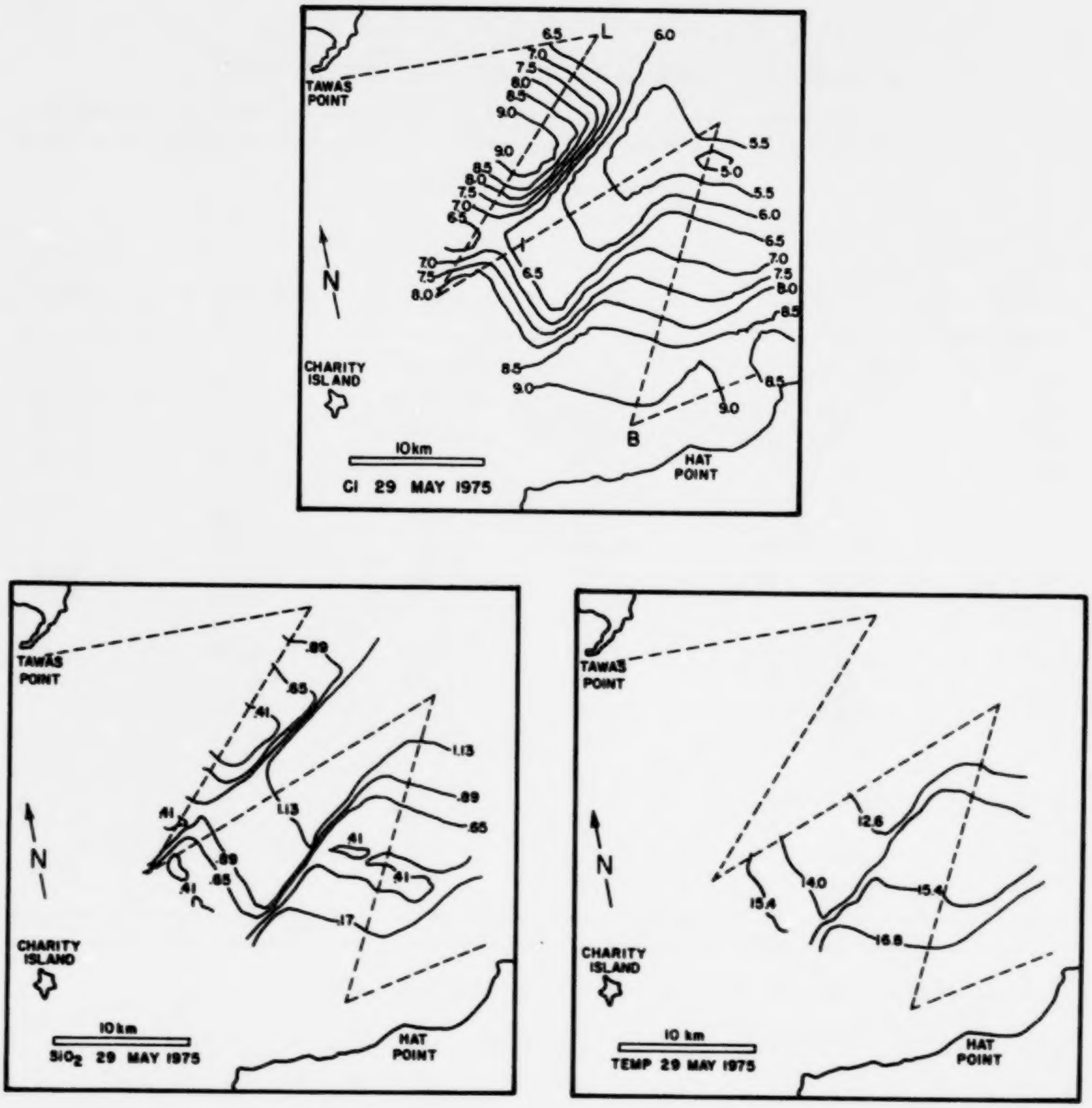
The August maps showed an irregular surface distribution of all variables in outer Saginaw Bay (Figures 6.9 and 6.10). Bay water, identified by high chloride content, was found on both sides of a wide tongue of lake water in the center of the outer bay. During the August cruise gentle SW

TABLE 6.3 AVERAGE VALUES OBSERVED DURING 1975

		Incubation Series			
			Location		
Cruise	Variable	Bay	Bay	Interface	Lake
May	chlorophyll a	3.02	2.07	2.46	0.86
May	^{14}C uptake	17.34	16.33	6.73	1.86
May	Assim. ratio	5.74	7.89	2.74	2.16
May	V_{max}	0.89	3.96	0.58	0.04
Late May	chlorophyll a	3.62	3.56	2.00	1.32
Late May	^{14}C uptake	12.61	9.54	4.99	2.91
Late May	Assim. ratio	3.48	2.68	2.50	2.20
Late May	V_{max}	1.12	0.13	2.93	0.15
Aug.	chlorophyll a	3.13	7.99	6.28	10.98
Aug.	^{14}C uptake	5.98	31.46	6.11	3.57
Aug.	Assim. ratio	1.91	3.94	0.97	0.33
Aug.	V_{max}	0.12	0.30	n.a.	0.05
Oct.	chlorophyll a	4.82	8.77	8.25	1.74
Oct.	^{14}C uptake	9.19	37.16*	9.94	8.48*
Oct.	Assim. ratio	1.91	4.24	1.20	4.87
Oct.	V_{max}	0.18	3.80	0.47	0.03

* Incubations done in on-deck artificial light incubator

Sample sizes: chlorophyll a = 4, ^{14}C uptake = 8, V_{max} = 1, Assim. ratio found by dividing ^{14}C uptake by chlorophyll a.



TAWAS POINT
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7.5
8.0
6.5
N
CHARITY ISLAND
8.5
9.0
9.0
8.5
B
10km
Cl 29 MAY 1975
HAT POINT
TAWAS POINT
.89
.65
.41
1.13
.89
.65
.41
1.13
.41
.41
.89
.65
.41
.17
N
CHARITY ISLAND
10km
SiO_2 29 MAY 1975
HAT POINT
TAWAS POINT
12.6
14.0
15.4
15.4
16.8
N
CHARITY ISLAND
10 km
TEMP 29 MAY 1975
HAT POINT

Figure 6.6. Contour maps from cruise 2 of 1975 study (29 May).

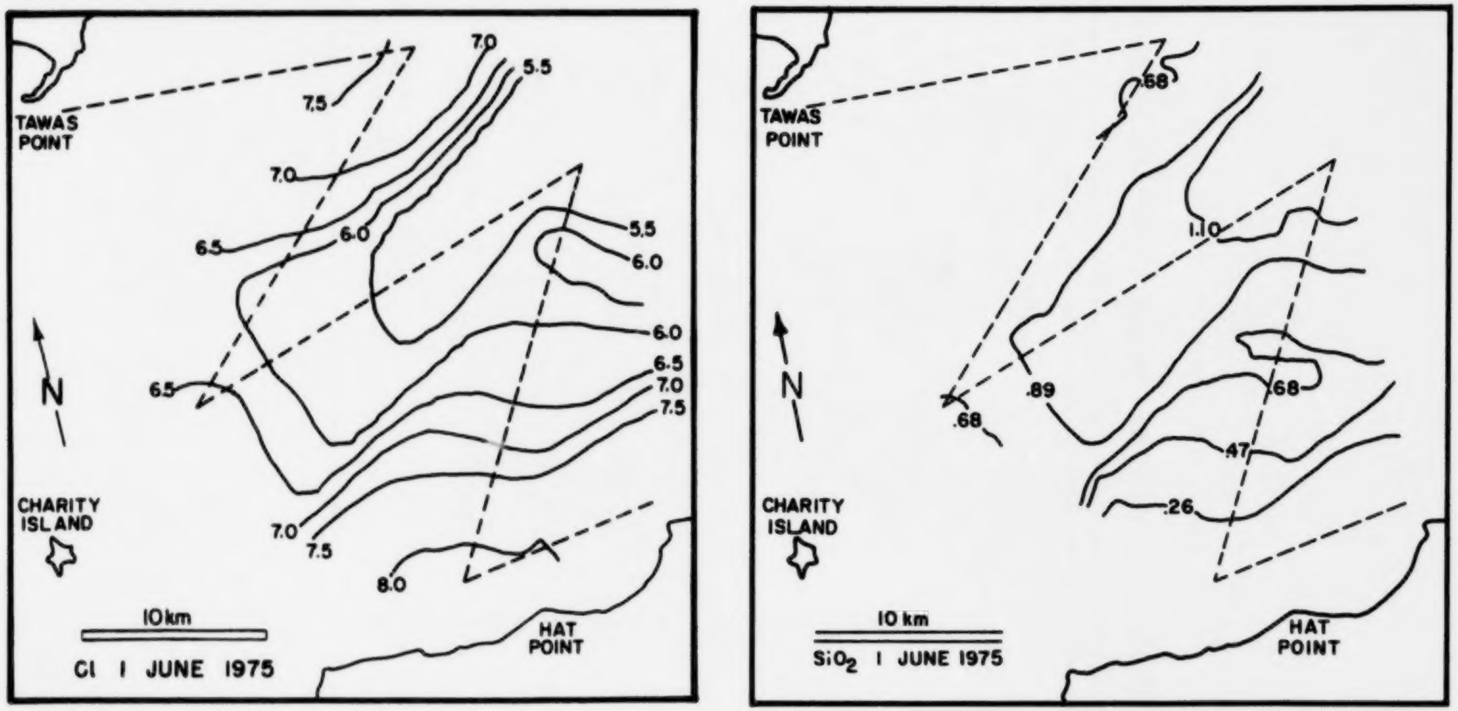

TAWAS POINT
CHARITY ISLAND
HAT POINT
N
10km
Cl 1 JUNE 1975
7.5
7.0
5.5
6.5
6.0
8.0
10 km
SiO_2 1 JUNE 1975
.68
1.10
.89
.47
.26

Figure 6.7. Contour maps from cruise 2 of 1975 study (1 June).

TABLE 6.4. DESCRIPTIVE MEASURES CRUISE #2 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	40	1.00	24.00	6.125	5.814
Secchi	25	3.50	13.00	7.860	3.996
Water Temp	40	4.40	18.40	11.74	5.109
pH	40	8.37	8.770	8.644	.1192
Chlorophyll a	40	.530	7.100	2.759	1.631
Silica	40	.020	1.500	.4495	.3841
Nitrate	40	200.	293.5	261.2	15.32
Ammonia	29	.700	47.17	18.36	13.72
Total Phosphorus	40	3.38	28.24	8.101	4.696
Total Soluble Phosphorus	40	1.63	10.47	2.651	1.395
Conductivity	40	2.00	2.450	2.310	.1055
Alkalinity	32	19.8	22.31	21.33	.7978
Chloride	39	5.43	8.910	7.257	.9761
Primary Production	32	1.16	20.09	7.51	5.69
Assimilation Ratio	16	.650	5.020	2.811	1.431
V_{max}	4	.130	2.930	1.082	1.315
Surface Light	19	840.	1840.	1345.	341.0
Extinction Coefficient	19	.110	.4800	.2768	.1003
Underwater Light	19	4.10	1050.	282.9	292.7

TABLE 6.5. PRODUCT-MOMENT CORRELATIONS AMONG VARIABLES FROM CRUISE 2, 1975, SOUTHERN LAKE HURON

VARIABLE															
DEPTH	1.000														
SECCHI	.330 (25)	1.000													
H2C TEMP	-.775 (40)	-.429 (25)	1.000												
PH	-.585 (40)	-.698 (25)	.409 (40)	1.000											
CHL A	-.245 (40)	-.776 (25)	.208 (40)	.418 (40)	1.000										
SIO2	.721 (40)	.728 (25)	-.711 (40)	-.865 (40)	-.361 (40)	1.000									
NO3 N	.615 (40)	.572 (25)	-.419 (40)	-.597 (40)	-.301 (40)	.654 (40)	1.000								
NH3 N	.177 (29)	.430 (14)	-.159 (29)	.052 (29)	-.246 (29)	.007 (29)	.108 (29)	1.000							
T PO4	-.318 (40)	-.476 (25)	.343 (40)	.390 (40)	.183 (40)	-.471 (40)	-.395 (40)	.138 (29)	1.000						
S PO4	-.169 (40)	-.327 (25)	.211 (40)	.218 (40)	.159 (40)	-.276 (40)	-.097 (40)	.036 (29)	.351 (40)	1.000					
CL	-.739 (39)	-.387 (24)	.776 (39)	.625 (39)	.088 (39)	-.834 (39)	-.493 (39)	-.100 (28)	.427 (39)	.271 (39)	1.000				
V MAX	-0. (4)	-.232 (4)	-.709 (4)	-.842 (4)	.400 (4)	.326 (4)	-.114 (4)	-1.000 (2)	.048 (4)	-.205 (4)	-.841 (4)	1.000			
EXT COEF	-.570 (19)	-.657 (19)	.470 (19)	.727 (19)	.700 (19)	-.776 (19)	-.595 (19)	-.520 (10)	.438 (19)	.171 (19)	.582 (19)	.195 (4)	1.000		
SUBLITE	-.659 (19)	.123 (19)	.711 (19)	.355 (19)	-.105 (19)	-.393 (19)	-.435 (19)	-.630 (10)	.240 (19)	.015 (19)	.637 (19)	.118 (4)	-.015 (19)	1.000	
C14	-.667 (16)	-.627 (16)	.705 (16)	.705 (16)	.611 (16)	-.773 (16)	-.560 (16)	-.694 (8)	.707 (16)	.593 (16)	.582 (16)	-.009 (4)	.618 (16)	.288 (16)	1.000
	DEP	SEC	TEMP	PH	CHL	SIO2	NO3	NH3	TPO4	SPO4	CL	VMAX	EXT	SUBL	C14

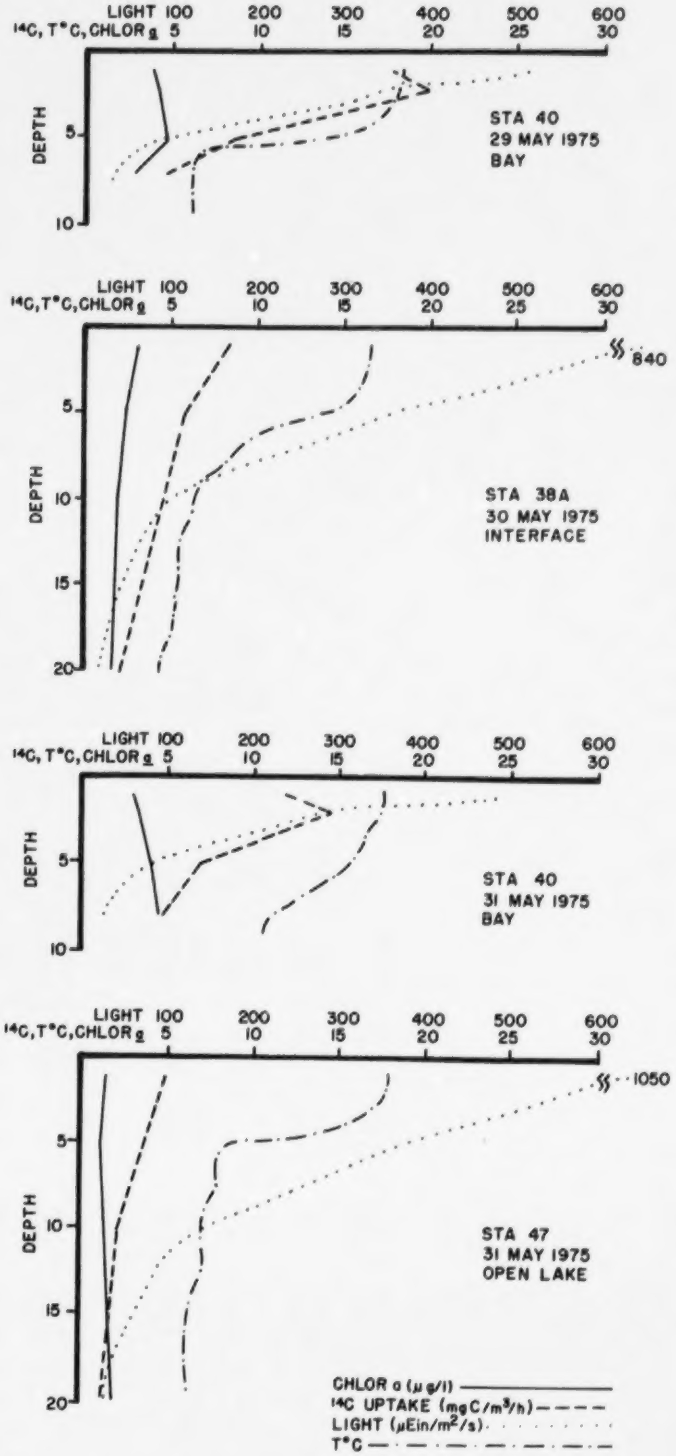
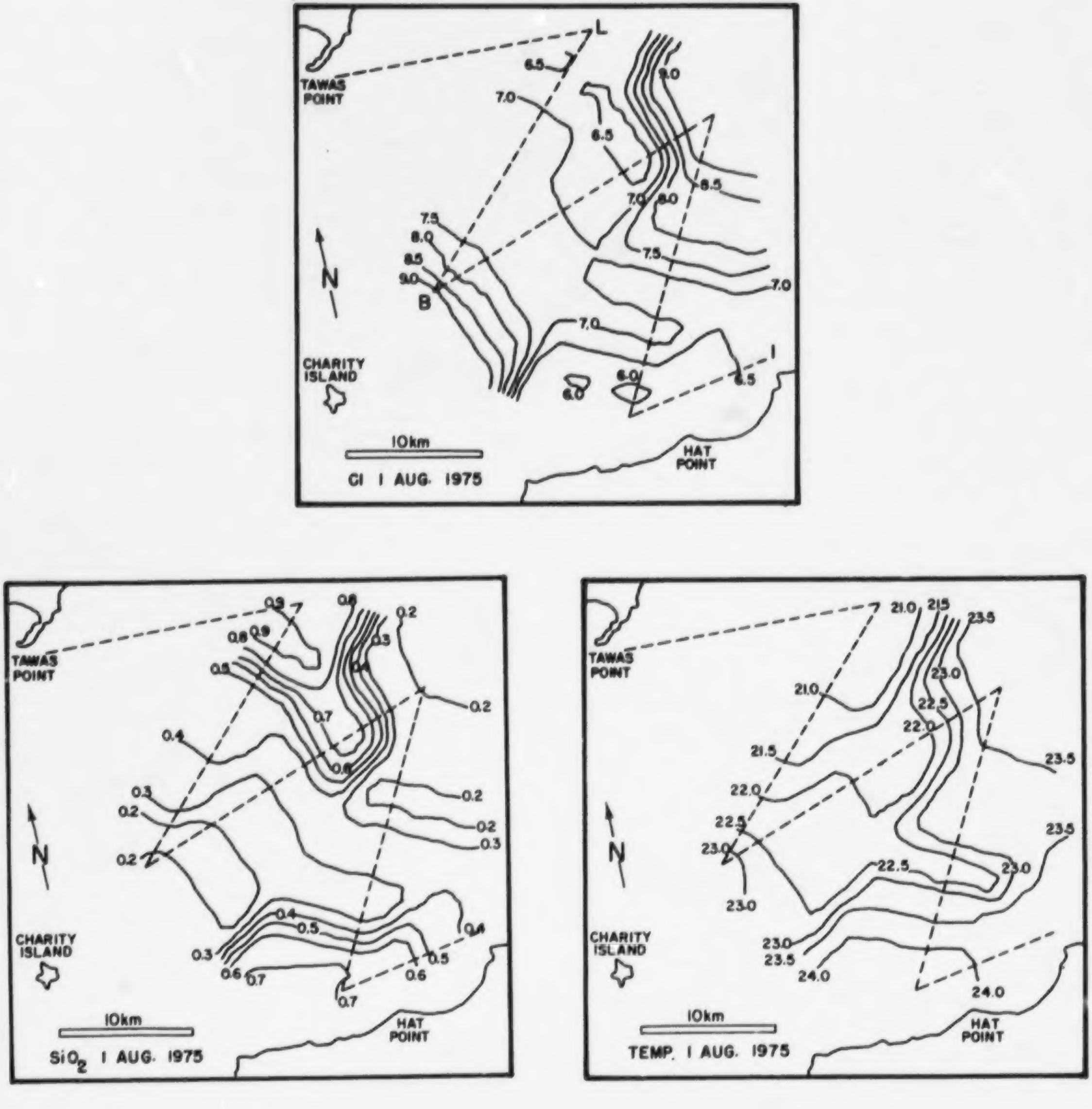


Figure 6.8. Results of the late May ^{14}C uptake profiles.


TAWAS POINT
CHARITY ISLAND
HAT POINT
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6.5
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Cl 1 AUG. 1975
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0.4
0.5
0.6
0.7
0.8
0.9
SiO2 1 AUG. 1975
21.0
21.5
22.0
22.5
23.0
23.5
24.0
TEMP. 1 AUG. 1975

Figure 6.9. Contour maps from cruise 3 of 1975 study (1 August).

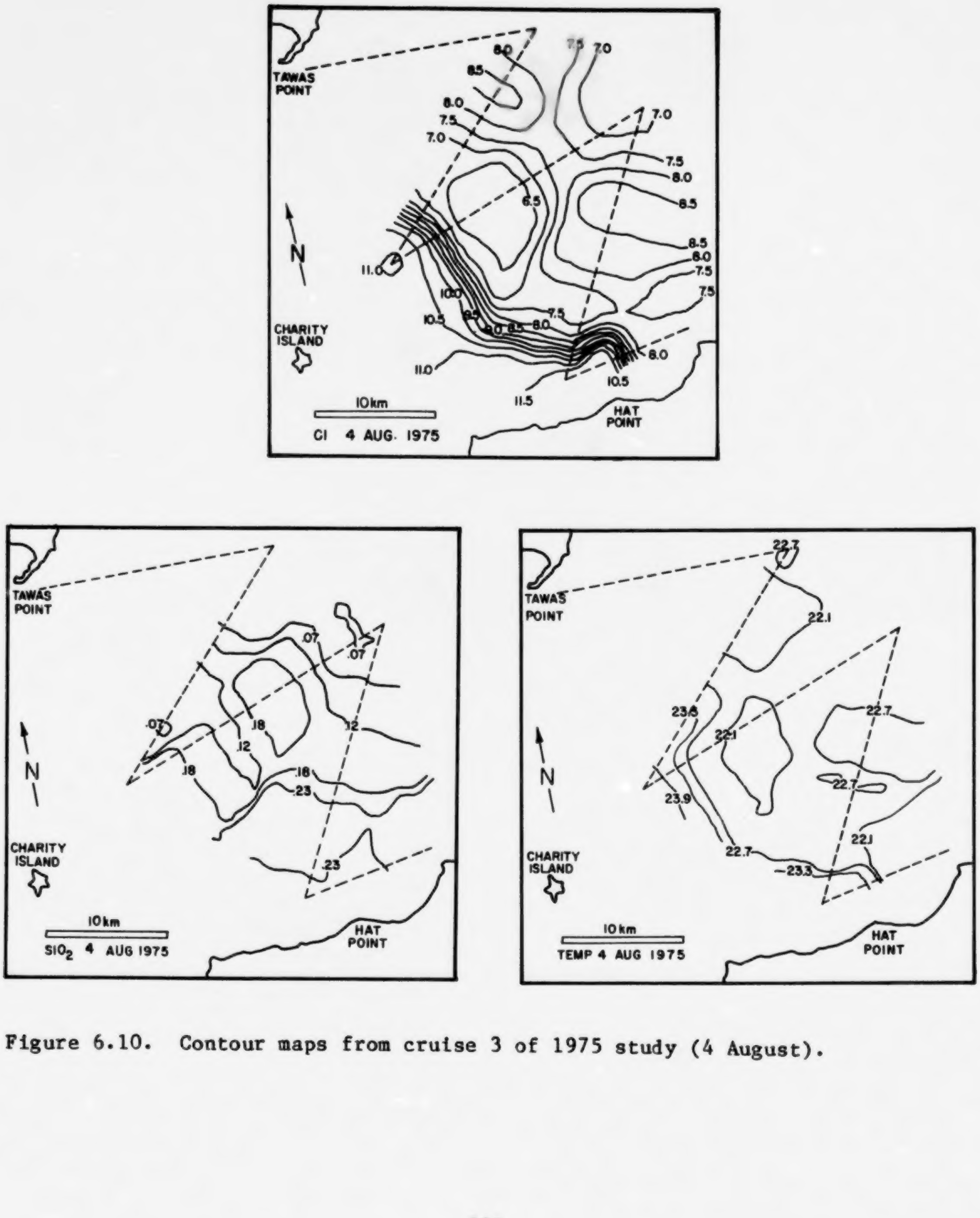

TAWAS POINT
CHARITY ISLAND
HAT POINT
N
10km
Cl 4 AUG. 1975
8.0
8.5
7.5
7.0
6.5
11.0
10.0
10.5
9.5
9.0
11.5
SIO2 4 AUG 1975
.07
.12
.18
.23
TEMP 4 AUG 1975
22.7
22.1
23.6
23.9
23.3

Figure 6.10. Contour maps from cruise 3 of 1975 study (4 August).

winds apparently had sufficient energy to move warm bay water farther into the open lake. The differences between the 1 August and 4 August maps suggest eutrophic bay water moved farther out of the bay on 1 August.

Considerable warming of surface water occurred between late May and August of 1975. The mean temperature increased to 16°C, while the average chlorophyll a value was also high at 6.5 g/l (Table 6.6). Although chlorophyll a biomass was large in August, much of this chlorophyll was found 10 m and deeper and ^{14}C uptake did not increase comparably (an average of 12.2 μg C/l/hr), yielding a low assimilation ratio (1.8). Dissolved silica levels continued to fall to where surface values were near analytical zero. Similar to 1974, in 1975 the August cruise showed a lowering of nearly all correlations among variables (Table 6.7). Correlations among nutrients, ^{14}C uptake, and chlorophyll a were lower except for a -0.87 correlation between ^{14}C uptake and nitrate. The predominant feature of the August 1975 cruise was high chlorophyll a biomass below 10 m at the open lake station. This deep, chlorophyll-rich layer occupied a niche not observed during the prior two cruises, which altered some of the correlations between plankton-related variables.

The early August cruise, a period of maximum annual temperatures and fully stratified conditions, was characterized by high chlorophyll a biomass (Table 6.3). Uptake of ^{14}C by phytoplankton which in the bay was high near the surface, but relatively low below the surface yielded a smaller average assimilation ratio in August than May or June. Figure 6.11 shows the highest concentrations of chlorophyll a near the bottom, but the highest levels of ^{14}C uptake near the surface. The interface station also displayed high chlorophyll a values as did the bay, but ^{14}C uptake levels were very low; the average assimilation ratio was close to 1.0 at the interface station (Table 6.3). The open lake station was apparently composed of water from open Lake Huron at the surface, and from Saginaw Bay below 5 m (Figure 6.11). Unusually high chlorophyll a and chloride levels at 10 m suggest the presence of bay water at 10 m. The average assimilation ratio was low in open lake water, but this may have been caused by an early morning incubation with an overcast sky providing little light at 10 m. Bacterial activity at all stations in August was fairly low.

October Cruise

The last cruise of 1975 (mid-October) was conducted during strong winds that shifted 180° between the two sampling dates -- from SW to NE. Despite the wind shift, the sets of maps from the beginning and end of the cruise were similar, showing a movement of water around the "thumb" of Michigan (Figures 6.12 and 6.13). The ranges of the three variables sampled were similar on both sampling dates; this result implied the October winds were creating a more homogeneous water column by mixing action, but did not cause any major shift in the distribution of water masses.

The October cruise occurred when shallow waters were homothermous, and a thermocline existed offshore at 30 m. The strong winds of early and mid-October had mixed the shallow part of the lake well, but only a moderate amount of cooling had occurred in that the average temperature was 12° C

TABLE 6.6. DESCRIPTIVE MEASURES CRUISE #3 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	45	1.00	30.00	7.644	6.146
Secchi	33	3.00	14.50	5.851	2.883
Water Temp	43	4.10	25.00	16.05	6.287
pH	43	8.04	8.850	8.584	.1481
Chlorophyll a	45	2.31	15.78	6.539	3.383
Silica	45	.030	1.320	.2622	.2507
Nitrate	45	43.1	288.8	175.9	56.69
Ammonia	41	6.520	41.39	17.25	9.371
Total Phosphorus	44	3.66	24.56	9.962	4.657
Total Soluble Phosphorus	45	1.77	31.47	5.865	6.002
Conductivity	43	2.01	2.400	2.138	.088
Alkalinity	29	19.3	26.14	20.91	1.245
Chloride	43	2.83	11.97	6.284	1.976
Primary Production	30	.560	86.47	12.16	19.79
Assimilation Ratio	15	.060	7.960	1.806	2.164
V_{max}	3	.050	.3000	.1566	.1289
Surface Light	22	150.	1650.	910.4	631.1
Extinction Coefficient	22	.170	.3700	.2750	.0677
Underwater Light	22	.100	1232.	185.1	289.7

TABLE 6.7. PRODUCT-MOMENT CORRELATIONS AMONG VARIABLES FROM CRUISE 3, 1975, SOUTHERN LAKE HURON

VARIABLE															
DEPTH	1.000														
SECCHI	.249 (33)	1.000													
H2O TEMP	-.875 (43)	-.201 (31)	1.000												
PH	-.781 (43)	-.358 (31)	.717 (43)	1.000											
CHL A	.057 (45)	-.095 (33)	.106 (43)	.074 (43)	1.000										
SIC2	.754 (45)	.262 (33)	-.579 (43)	-.654 (43)	.061 (45)	1.000									
NO3 N	.636 (45)	.608 (33)	-.627 (43)	-.767 (43)	-.183 (45)	.443 (45)	1.000								
NH3 N	.100 (41)	-.295 (29)	.040 (39)	-.088 (39)	.507 (41)	.232 (41)	-.027 (41)	1.000							
T PO4	-.149 (44)	-.425 (32)	.357 (42)	.343 (42)	.412 (44)	.063 (44)	-.426 (44)	.373 (40)	1.000						
S PO4	.014 (45)	-.154 (33)	.058 (43)	.006 (43)	.194 (45)	.391 (45)	-.285 (45)	.382 (41)	.337 (44)	1.000					
CL	-.308 (43)	-.077 (31)	.416 (41)	.495 (41)	.445 (43)	-.189 (43)	-.356 (43)	.251 (40)	.492 (42)	-.136 (43)	1.000				
V MAX	-0. (3)	-.951 (3)	.591 (3)	.884 (3)	.766 (3)	.665 (3)	-.999 (3)	-.369 (3)	.973 (3)	.926 (3)	-.896 (3)	1.000			
EXT COEF	-.144 (22)	-.477 (22)	.179 (20)	.300 (20)	.549 (22)	-.146 (22)	-.380 (22)	.433 (19)	.763 (21)	.101 (22)	.508 (22)	.962 (3)	1.000		
SUBLITE	-.534 (22)	-.067 (22)	.442 (20)	.452 (20)	-.364 (22)	-.310 (22)	-.343 (22)	-.381 (19)	-.123 (21)	-.113 (22)	.120 (22)	.113 (3)	-.213 (22)	1.000	
C14	-.453 (15)	-.501 (15)	.526 (15)	.764 (15)	.089 (15)	-.188 (15)	-.872 (15)	.005 (14)	.657 (14)	-.040 (15)	.200 (15)	.965 (3)	.456 (15)	.264 (15)	1.000
	DEP	SEC	TEMP	PH	CHL	SIC2	NO3	NH3	TPO4	SPO4	CL	VMAX	EXT	SUBL	C14

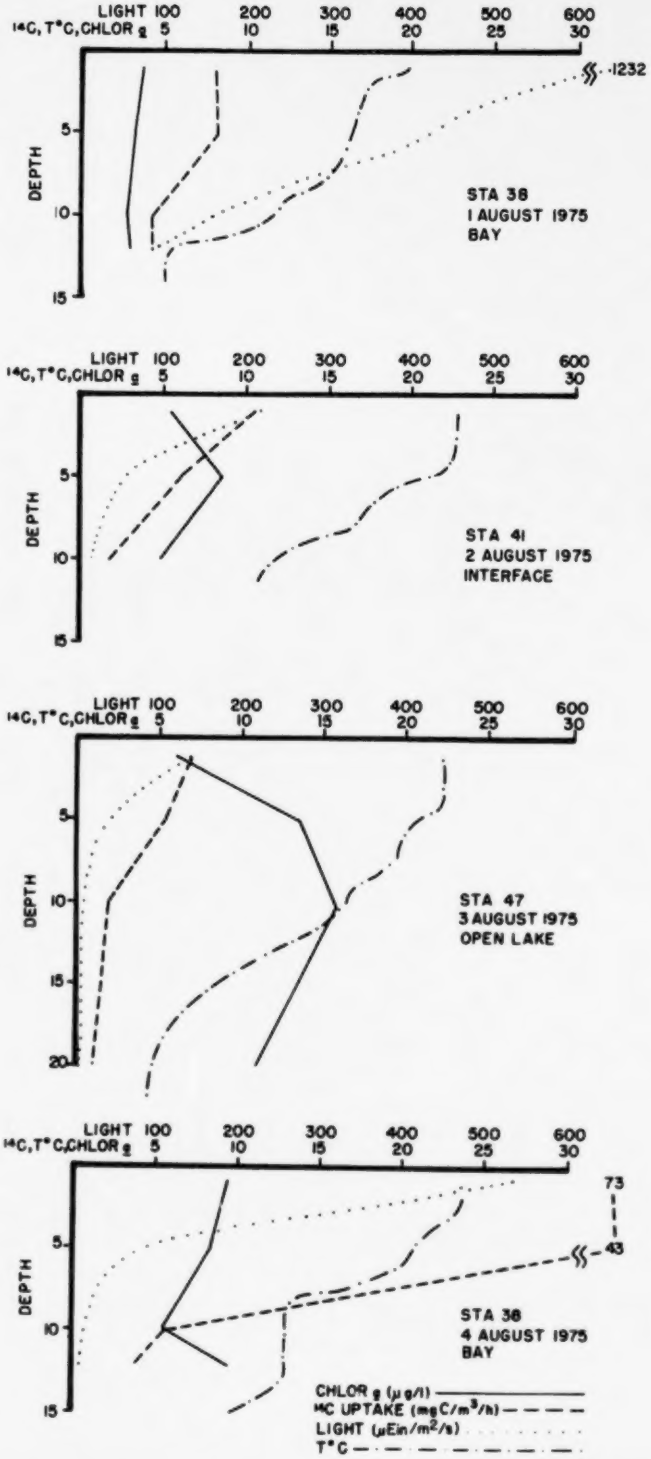
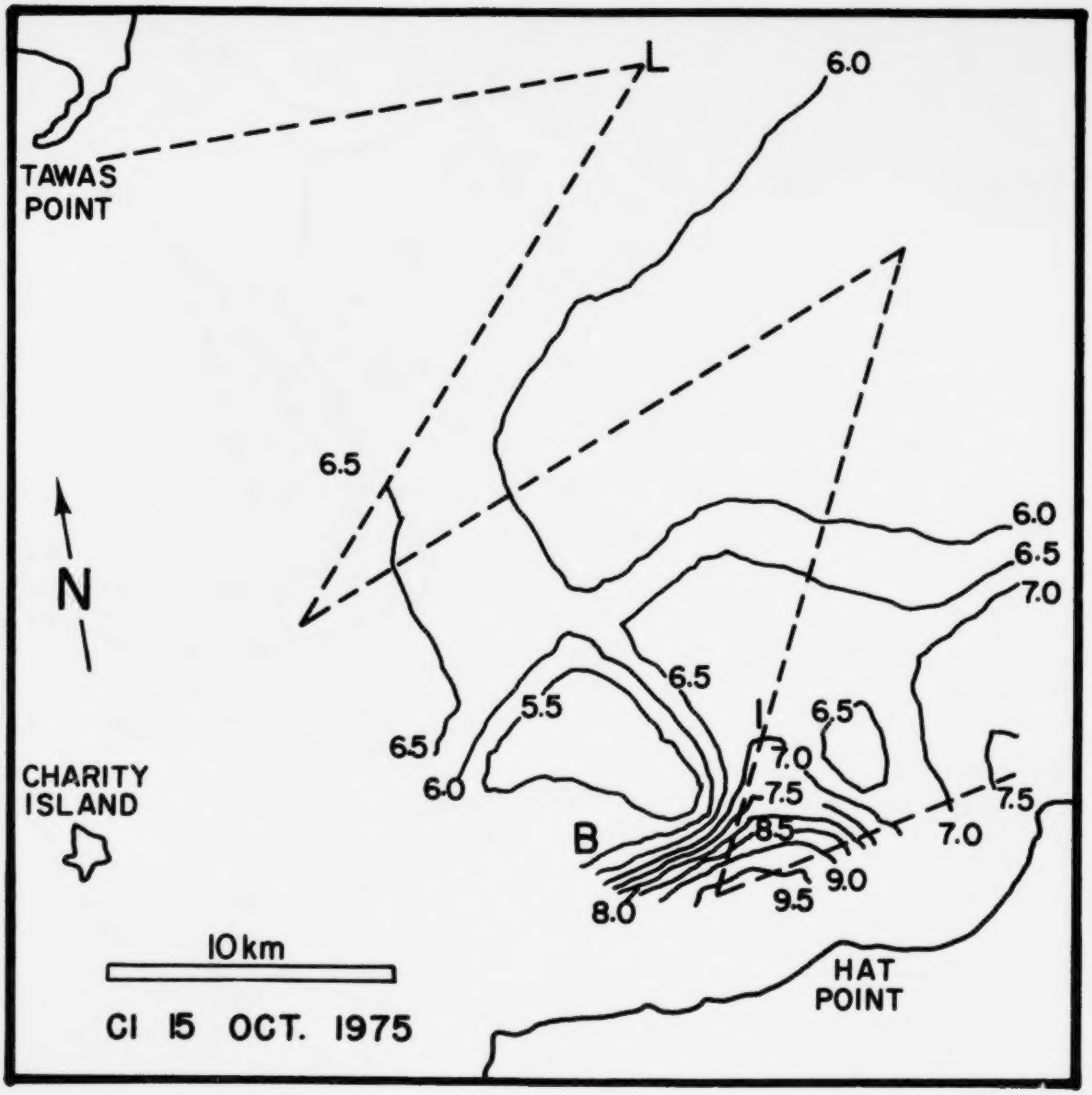


Figure 6.11. Results of the early August ^{14}C uptake profiles.


TAWAS POINT
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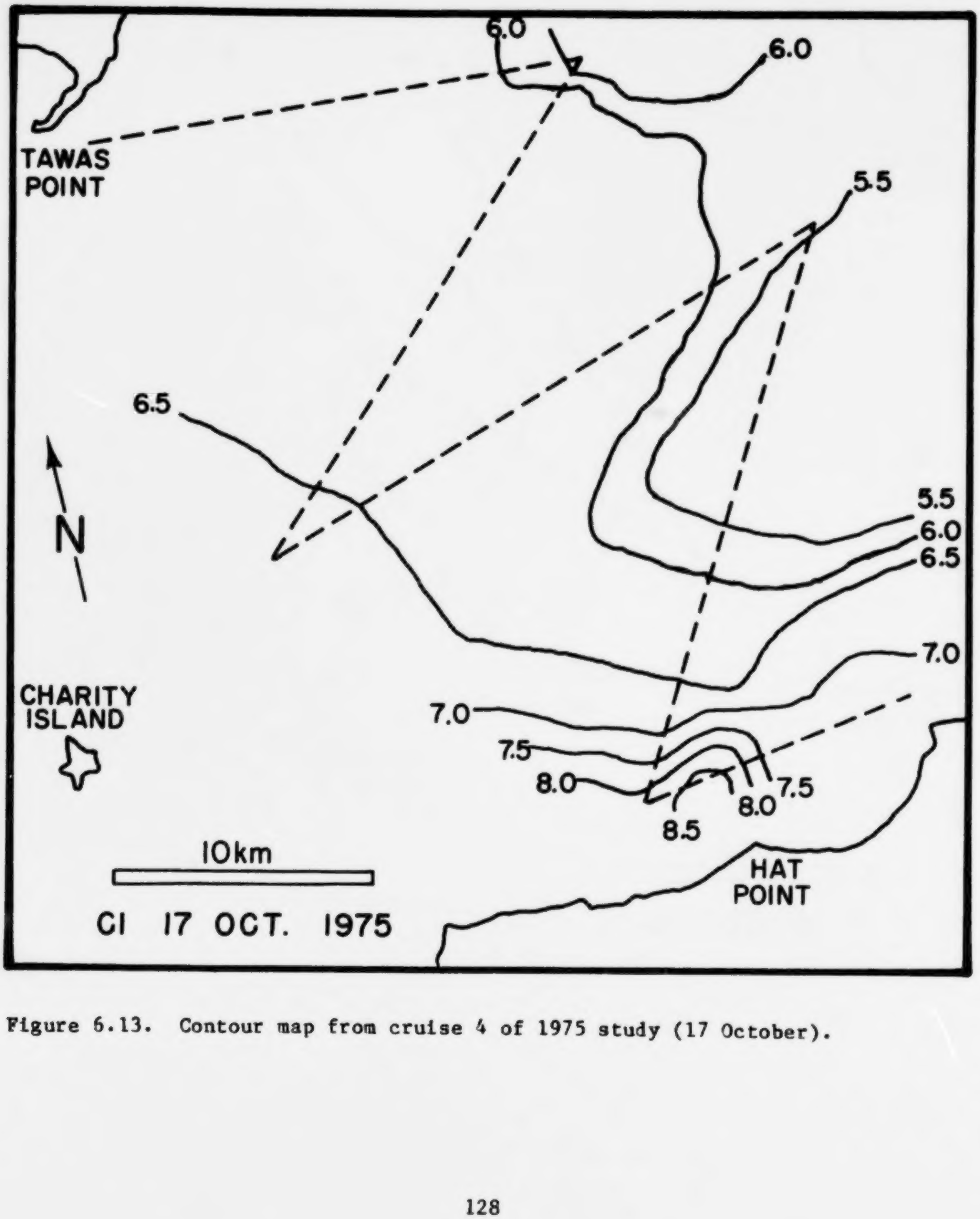
10km
HAT POINT
CI 15 OCT. 1975

Figure 6.12. Contour map from cruise 4 of 1975 study (15 October).



6.0
6.0
TAWAS POINT
5.5
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CHARITY ISLAND
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8.5
10km
HAT POINT
CI 17 OCT. 1975

Figure 6.13. Contour map from cruise 4 of 1975 study (17 October).

(Table 6.8). Mixing of the water column had apparently brought sufficient nutrients and plankton to the surface to stimulate some algal growth. Average nutrient concentrations were lower in October than August implying continued phytoplankton growth and nutrient utilization (Table 6.8). The correlations from the October data set were similar to the August data in that they were generally lower than the first two cruises (Table 6.9). In October, all correlations among ^{14}C uptake and nutrients were lower than in May, June, or August.

Chlorophyll a biomass was higher in October than August at all but the open lake station (Fig. 6.14). There was a comparable increase in ^{14}C uptake at these stations that increased the assimilation ratio from August (Table 6.3). However, rough seas prevented anchoring the ship for two incubation series, thus ^{14}C uptakes were made in an artificial-light incubator onboard the ship; assimilation ratios from the on-deck incubations are not comparable to *in situ* results. The artificial light source approximated 4-5 m in bay water and 10-12 m in lake water.

Differences Among Water Quality Regions

In addition to the cruise-by-cruise analysis of the chemical, physical, and biological data, analyses were carried out on the basis of water quality: bay water, interface water, and open lake water. The analyses did not reveal any unusual aspects of Lake Huron limnology but did confirm some preconceived ideas of Saginaw Bay and Lake Huron. Tables 6.10-6.12 give descriptive measures of the three types of water. Table 6.13 compares the means of some of the variables measured in the three water types by way of t-tests. These t-tests show the large differences between lake and bay waters and somewhat more subtle differences among the lake to interface and bay to interface comparisons.

Simple means show Saginaw Bay water had the warmest temperatures (13.3°C), the highest chlorophyll a biomass (4.7 μg/l), the highest ^{14}C uptake (17 μgC/l/hr), the highest assimilation ratio (4.1), and the lowest silica (.223 mg/l) and nitrate levels (212 μg/l). The lower nutrient levels were surprising in that bay water is usually characterized by high nutrient loads (Bierman and Dolan, 1976). But, the area we studied was the outer bay mouth where inputs of nutrients were low and phytoplankton growth was high.

The interface stations were representative as interface water; these stations had values of temperature, chlorophyll a, and nutrients in between the bay stations and open lake stations (Table 6.11). However, for two variables the interface water was not intermediate in value to the bay and lake stations: low ^{14}C uptake was found at these stations, producing the lowest assimilation ratio. Table 6.13 shows the ^{14}C uptake levels were significantly different between bay and interface waters, while chlorophyll a levels were not different. Additionally, the bacterial crop at the interface was very active, almost as active as the bay bacterial crop. We speculate *a posteriori* that the interface area was a zone which often received senescent phytoplankton crops washing out from the bay.

The open lake data appeared representative of the oligotrophic water

TABLE 6.8. DESCRIPTIVE MEASURES CRUISE #4 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	16	1.0000	30.00	7.644	6.146
Secchi	16	2.00	6.000	3.625	1.522
Water Temp	16	12.3	13.80	12.67	.6708
pH	16	8.29	8.760	8.405	.1085
Chlorophyll _a_	16	1.49	11.28	5.893	3.218
Silica	16	.030	.2900	.0969	.074
Nitrate	16	80.0	203.2	135.5	45.10
Ammonia	16	4.45	24.62	15.06	5.382
Total Phosphorus	16	4.41	37.91	16.58	10.33
Total Soluble Phosphorus	15	1.53	16.57	4.136	3.890
Conductivity	16	2.05	2.490	2.275	.1478
Alkalinity	16	19.3	22.65	20.92	.9396
Chloride	16	5.14	10.70	7.620	1.836
Primary Production	32	1.01	39.51	16.19	14.17
Assimilation Ratio	16	.132	7.341	3.216	2.136
V_{max}	4	.033	3.803	1.121	1.797

TABLE 6.9. PRODUCT-MOMENT CORRELATIONS AMONG VARIABLES FROM CRUISE 4, 1975, SOUTHERN LAKE HURON

VARIABLE	DEP	SEC	TEMP	PH	CHL	SIO2	NO3	NH3	TPO4	SPO4	CL	VMAX	C14
DEPTH	1.000												
SECCHI	.260 (16)	1.000											
H2O TEMP	-.195 (16)	-.049 (16)	1.000										
PH	-.248 (16)	.641 (16)	.092 (16)	1.000									
CHL A	-.132 (16)	-.864 (16)	-.199 (16)	-.524 (16)	1.000								
SIO2	.176 (16)	-.361 (16)	-.217 (16)	-.138 (16)	.491 (16)	1.000							
NO3 N	.266 (16)	.953 (16)	-.182 (16)	.644 (16)	-.753 (16)	-.118 (16)	1.000						
NH3 N	-.407 (16)	-.563 (16)	-.285 (16)	.002 (16)	.493 (16)	.080 (16)	-.563 (16)	1.000					
T PO4	-.094 (16)	-.693 (16)	-.280 (16)	-.379 (16)	.772 (16)	.780 (16)	-.468 (16)	.299 (16)	1.000				
S PO4	-.218 (15)	-.275 (15)	.282 (15)	-.097 (15)	.149 (15)	-.182 (15)	-.338 (15)	.247 (15)	-.062 (15)	1.000			
CL	-.050 (16)	-.781 (16)	-.261 (16)	-.425 (16)	.822 (16)	.744 (16)	-.584 (16)	.417 (16)	.878 (16)	.056 (15)	1.000		
VMAX	-0. (4)	-.700 (4)	-.348 (4)	-.960 (4)	.149 (4)	-.319 (4)	-.768 (4)	.947 (4)	.432 (4)	.989 (4)	.415 (4)	1.000	
C14	-.398 (16)	-.589 (16)	-.295 (16)	-.494 (16)	.488 (16)	-.220 (16)	-.640 (16)	.561 (16)	.279 (16)	.223 (15)	.246 (16)	.981 (4)	1.000

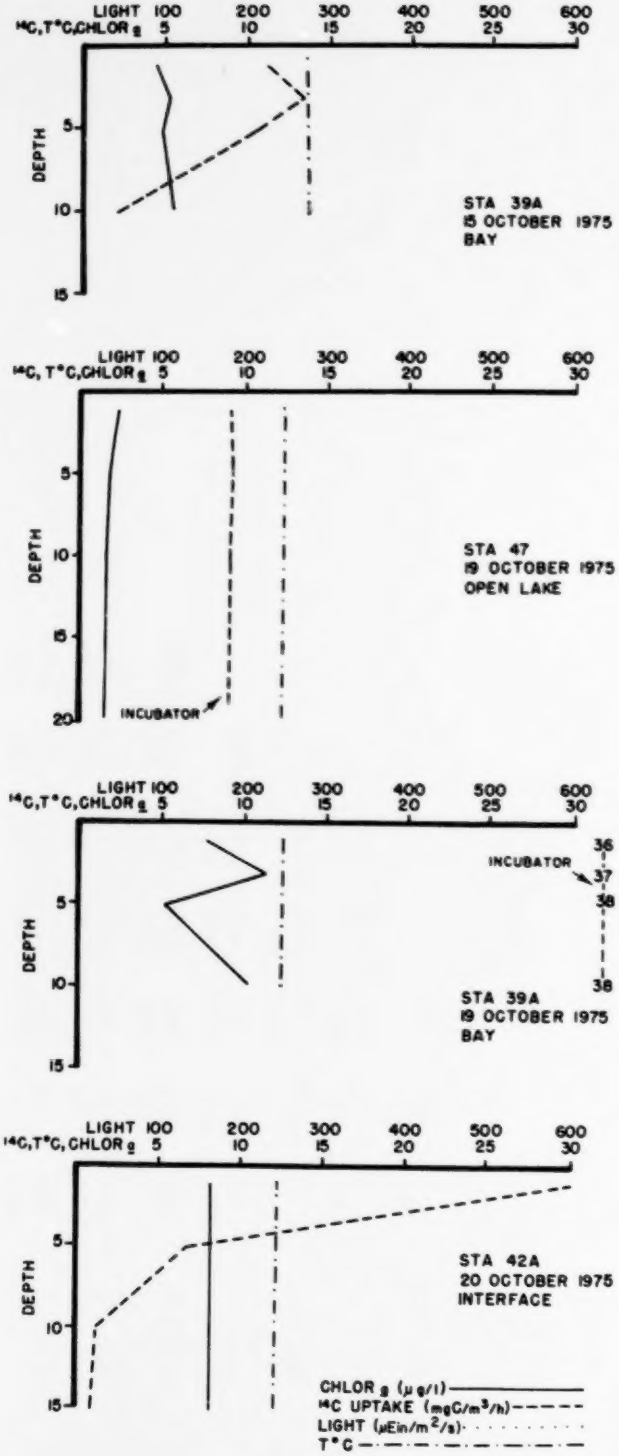

Figure 6.14. Results of the October ^{14}C uptake profiles.

TABLE 6.10. DESCRIPTIVE MEASURES BAY STATIONS 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	78	1.00	15.00	5.859	4.123
Secchi	48	2.00	8.500	4.431	1.580
Water Temp	78	5.80	25.80	13.29	5.744
pH	78	8.29	8.850	8.602	.1407
Chlorophyll a	78	1.29	14.22	4.722	2.856
Silica	78	.020	.6900	.2234	.1639
Nitrate	78	43.1	334.2	209.0	71.23
Ammonia	69	.700	47.17	15.95	9.921
Total Phosphorus	78	3.66	28.24	10.43	4.924
Total Soluble Phosphorus	78	1.63	26.10	4.274	3.670
Conductivity	78	2.01	2.480	2.259	.1414
Alkalinity	58	19.3	23.45	21.40	.9119
Chloride	77	2.83	11.97	7.118	1.762
Primary Production	66	1.87	86.47	17.15	15.33
Assimilation Ratio	33	.390	14.13	4.090	2.996
V_{max}	09	.120	3.960	1.492	1.615
Surface Light	29	430.	1840.	1135.	424.3
Extinction Coefficient	29	.170	.4800	.3051	.073
Underwater Light	29	3.10	1232.	239.2	296.2

TABLE 6.11. DESCRIPTIVE MEASURES INTERFACE STATIONS 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	21	1.00	20.00	7.428	6.112
Secchi	21	3.00	11.00	5.790	2.699
Water Temp	21	4.60	23.10	12.19	6.022
pH	21	8.37	8.780	8.502	.1193
Chlorophyll a	20	.530	8.660	4.468	2.916
Silica	21	.090	1.500	.4881	.3775
Nitrate	21	123.	293.5	212.1	63.38
Ammonia	18	.880	30.69	14.56	7.563
Total Phosphorus	20	3.49	37.91	13.54	10.49
Total Soluble Phosphorus	20	1.63	18.74	4.686	4.086
Conductivity	21	2.00	2.490	2.253	.1249
Alkalinity	19	19.1	22.48	20.78	.7773
Chloride	19	4.16	10.70	7.127	1.770
Primary Production	30	1.01	30.58	7.12	7.20
Assimilation Ratio	14	.130	4.140	1.863	1.355
V_{max}	3	.470	2.930	1.326	1.389
Surface Light	11	310.	1840.	1019.	673.6
Extinction Coefficient	11	.130	.3900	.2809	.076
Underwater Light	11	.800	840.0	176.3	254.9

TABLE 6.12. DESCRIPTIVE MEASURES OPEN LAKE STATIONS 1975 SOUTHERN LAKE HURON

Variable	N	Minimum	Maximum	Mean	Std. Dev.
Depth	28	1.0000	40.000	10.750	10.377
Secchi	28	6.0000	14.500	9.6964	2.7633
Water Temp	26	3.1000	22.200	8.0885	6.0971
pH	26	8.0400	8.7600	8.4538	.14037
Chlorophyll *a*	28	.74000	15.780	3.1743	4.0784
Silica	28	.030	1.3200	.63321	.42581
Nitrate	28	167.30	368.20	251.55	48.536
Ammonia	25	3.8000	41.390	16.437	10.997
Total Phosphorus	28	3.0600	16.160	6.8668	3.6260
Total Soluble Phosphorus	28	1.5300	31.470	4.4129	5.7032
Conductivity	26	1.8200	2.3100	2.1650	.10289
Alkalinity	19	19.380	26.140	20.662	1.5359
Chloride	28	2.4600	8.5100	5.9529	1.4140
Primary Production	32	.56000	9.0200	4.20	3.03
Assimilation Ratio	16	.060	5.6200	2.5437	1.8979
V_{max}	4	.030	.15000	.0675	.056
Surface Light	24	69.500	1470.0	750.77	524.87
Extinction Coefficient	24	.11000	.32000	.21458	.063
Underwater Light	24	.040	1050.0	173.80	247.58

TABLE 6.13. COMPARISONS OF MEANS FROM BAY, INTERFACE AND OPEN LAKE WATER BY T-TESTS. MEANS USED IN COMPARISONS ARE FROM ALL CRUISES. CHLOROPHYLL _A_ DATA WERE SUBJECT TO A NATURAL LOG TRANSFORMATION TO CORRECT EXCESSIVE SKEW AND KURTOSIS

	T-statistic		
Variable	Bay vs. Interface	Lake vs. Interface	Bay vs. Lake
Temperature	0.707 n.s.	2.372*	3.933***
Extinction Coefficient	1.212 n.s.	3.016**	6.543***
Chloride	0.238 n.s.	3.154*	4.951***
pH	2.787**	0.418 n.s.	3.307***
Silica	2.754**	0.718 n.s.	3.880***
Nitrate	0.047 n.s.	1.939 n.s.	2.599***
Total Phosphorus	1.189 n.s.	3.113**	5.805***
Chlorophyll _a_	1.086 n.s.	4.228*	8.407***
^{14}C uptake	3.611*	1.164 n.s.	4.319***
V_{max} (glucose)	0.163 n.s.	1.547 n.s.	2.583*

Significance probability levels: n.s. = non-significant, * = 0.5, ** = 0.01, and *** = 0.001.

found in most of Lake Huron: cold, low in chlorophyll a, and high in nutrients (Table 6.12). High ^{14}C uptake was occasionally found producing moderate assimilation ratios. Bacterial activity was extremely low in the open lake perhaps due to the low temperatures and/or the low level of biomass to serve as a substrate.

DISCUSSION

Saginaw Bay appears to behave much like a reactor with an input of nutrients (at the southern end), dilution, and development of large plankton crops. Water, which moved toward the open lake, apparently stimulates phytoplankton blooms, with these blooms rapidly diminishing in the outer bay. Bay stations, taken near the outer edge of bay water, were readily identifiable because of high concentrations of conservative tracers as temperature, chloride, sulfate, and conductivity. But, the biological reactor (the bay) reduced some of the nutrient levels and increased chlorophyll a biomass by the time water reached the outer bay. These events were reflected in the differences between the bay and open lake stations; the bay water had higher chlorophyll a, ^{14}C uptake, assimilation ratios, temperature, chloride and pH, but lower nitrate, ammonia, total soluble phosphorus, silica, and Secchi values than open lake stations (Tables 6.10 and 6.12). Some of the difference between bay and open lake stations may have been because of the presence of hypolimnetic samples in the lake stations, but the majority of open lake samples were epilimnetic.

The interface station yielded concentrations of dissolved nutrients which generally fell between the open lake and bay values, but high phytoplankton biomass with the low ^{14}C uptake produced the lowest assimilation ratio of the three areas studied. These data implied that plankton in the interface were not actively growing, but, continuing with the reactor analogy, were in a washout phase. The concept of a washout crop was further supported by high levels of glucose assimilation by bacteria. Inactive phytoplankton are known as a suitable and abundant substrate for bacterial attachment and growth (Paerl et al., 1975). Assuming the interface between Saginaw Bay and Lake Huron represented a zone of phytoplankton washout, the question arose as to what extent did bay water influence the southern end of Lake Huron. This study did not provide enough data to answer that question, but taken with the 1974 data did allow some speculation. The high amount of suspended material from the bay does, on occasion, move beyond the bay around the thumb of Michigan's southern peninsula as was observed at the lake station during the August cruise. But, wind from the north and east will hold water in the bay allowing the suspended material to settle out and phytoplankton to be heavily grazed. The dissolved material, on the other hand, must eventually leave the bay and mix into the southern end of the lake. The change in Lake Huron water quality due to the influence of Saginaw Bay cannot be evaluated in simple terms, but depends on the variable in question, e.g. whether soluble or particulate in form.

Influence of Seasonal Sampling

Although the effect of seasonal changes was not analyzed statistically, seasonal differences were evident at all sampling locations, with the open lake stations showing the largest changes (Table 6.3). The coefficient of variation for the bay station chlorophyll a mean was 60 percent, while the coefficient of variation for the lake station mean was more than 129 percent. The conclusion was that the bay represents a more biologically active but consistent environment. The 1974 data show that much of the variability in the bay was the result of patchiness rather than seasonality. However, the 1975 sampling effort may have been biased because the onset of thermal stratification had occurred in the bay just before the first cruise, while the same event in the open lake was well bracketed by the four cruises. In addition, the open lake station suffered an intrusion of bay water during the August cruise which increased the variance of that station.

Vertical Distributions of Phytoplankton-Related Variables

The vertical distribution of ^{14}C uptake was, in part, a function of chlorophyll a biomass and submarine light. Submarine light attenuation was primarily a function of location; the average extinction coefficient ranged from 0.21 for the open lake stations, 0.28 for the interface stations, and 0.30 for the bay stations. Thus, we considered the depth distribution of chlorophyll a as the more important plankton-related variable.

The trend in the depth distribution of chlorophyll a was similar to the influence of seasonality; the bay station had the most consistent chlorophyll a profile from cruise to cruise, while the open lake station changed more. All the stations sampled in the first two cruises showed homogeneous chlorophyll a profiles (Figures 6.5 and 6.8). The open lake station was either homothermous or recently stratified during these early cruises, thus a homogeneous profile was the expected result. The bay station provided a uniform chlorophyll a profile on almost every occasion. By August maximum chlorophyll a concentrations were found below 5 m at the open lake station (Figure 6.11). In October this deep layer had disappeared with the deepening of the thermocline and mixing by strong winds. The interface station produced chlorophyll a profiles which were intermediate to the open lake and bay stations. The shape of these profiles could have been due to aging plankton populations settling out of the water column as bay water moved out into the open lake. The sampling frequency in terms of numbers of cruises in 1975 was too low to draw many more conclusions than these: chlorophyll a was generally evenly distributed with depth in bay water, a definite seasonal depth distribution of chlorophyll a was found at the open lake station, and the chlorophyll a-depth distribution was uneven at the interface stations.

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SECTION 7

INFLUENCES OF SPRING NEARSHORE THERMAL BAR

by Curtiss O. Davis, Claire L. Schelske and Russell G. Kreis, Jr.

In 1974, the Great Lakes Research Division conducted eight surveys of nutrient chemistry and phytoplankton in the southern half of Lake Huron as part of the Upper Lakes Reference Study for the International Joint Commission (IJC). During the first two cruises (28 April-3 May and 14-17 May), high nitrate and total phosphorus levels were observed along the Ontario shore between Point Clark and Kettle Point. The highest values, nitrate, 1330 μg N/l and total phosphorus, 16.7 μg P/l, were about three times the open lake values at that time. These levels decreased with time, and by the fourth cruise, June 22-25, nutrient levels in the Point Clark to Kettle Point region were similar to other nearshore areas (Section 3).

In the same year, the Ontario Ministry of the Environment surveyed the Ontario nearshore regions of Lake Huron and found the Point Clark to Kettle Point region to have the highest total phosphorus and total nitrogen levels of any nearshore area studied, particularly during the spring (International Joint Commission, 1977). They found average values of 29 μg P/l for total phosphorus and 902 μg N/l for total nitrogen during spring, about twice the levels observed along the adjacent shorelines.

Physical and chemical characteristics of the Maitland, Bayfield, and Ausable rivers, which empty into Lake Huron between Point Clark and Kettle Point were investigated by the Ontario Ministry of the Environment (1978). These rivers drain 2460, 466, and 865 sq km, respectively, of primarily agricultural lands. During the first four months of 1975, the Maitland, Bayfield, and Ausable (via the diversion cut at Port Franks) rivers carried 24.5, 27.7, and 32.3 metric tons of phosphorus and 2160, 973, and 1500 metric tons of nitrate-nitrogen, respectively, into Lake Huron. Conceivably, if most of these nutrients were retained in the nearshore zone between Point Clark and Kettle Point, the river input could account for much of the high spring nutrient levels observed in that region.

As is typical of large lakes in the temperate zone, the Laurentian Great Lakes develop a thermal bar in the spring and fall (Rodgers, 1965, 1966; Huang, 1972). Both Rodgers and Huang note that the spring thermal bar strongly inhibits exchange between the warm water nearshore and the cold central lake water mass. Materials entering the lake from rivers or other discharges are confined to the nearshore zone by the thermal bar. Similarly, the spring phytoplankton bloom has been observed to initially develop in nearshore waters and then remain on the nearshore side of the thermal bar (Nalewajko, 1967; Stoermer, 1968).

In 1975, a four-day cruise was conducted from 29 April-2 May to study a segment of the Ontario nearshore region where high nutrients had been observed the previous year and a comparable section of the Michigan nearshore near Harbor Beach where no high nutrient levels had been observed (Section 3). The objective was to determine how far the elevated nutrient levels extend into the lake and to examine the role of the thermal bar in confining phytoplankton and nutrients to the nearshore zone. Some of the 1974 southern Lake Huron survey data are also presented to amplify the results from the 1975 cruise.

MATERIALS AND METHODS

The 1974 southern Lake Huron surveys and the 1975 nearshore cruise were conducted on the R/V ROGER R. SIMONS operated by the U.S. Environmental Protection Agency. Temperature profiles were made using a mechanical bathythermograph. Discrete water samples were taken with Niskin bottles and analyzed for pH, specific conductance, and chlorophyll a (extracted in 90% acetone) by fluorometric analysis (Strickland and Parsons, 1968). Carbon-14 uptake was measured following Schelske and Callender (1970) except that an artificial light (cool, white fluorescent) incubator was used with a light intensity of 118 $\mu E/m^2/sec$. The incubator was cooled with lake water pumped from a depth of 1 m. Nutrient concentrations were measured using a Technicon Autoanalyzer system II for nitrate plus nitrite, silica (Armstrong et al., 1967), ammonia (Slawyk and MacIsaac, 1972), and orthophosphate (Murphy and Riley, 1962) and an Autoanalyzer I system for total phosphorus (Menzel and Corwin, 1965). Chloride was also analyzed using the Autoanalyzer II system (Technicon, 1972). Phytoplankton cell counts were made according to Stoermer et al. (1971) except that only two radii were counted instead of six.

During the 1975 nearshore survey, underway "maps" (Kelley, 1976) of temperature, chlorophyll fluorescence, chloride, nitrate, and silica were made of the nearshore zones near Bayfield, Ontario, and Harbor Beach, Michigan. Water from 1 m depth was sampled continuously as the ship steamed a zig-zag course through the area to be studied. Water was pumped into the laboratory, passing first through a debubbler containing a thermistor to measure temperature, then through a Turner model 111 fluorometer equipped with a flow-through door to measure *in vivo* chlorophyll fluorescence (Strickland and Parsons, 1968). On the outlet side of the fluorometer, the water hose was tapped with a small tube that carried the water to the Autoanalyzer II system. The water was passed through an inline HA Millipore filter and was analyzed for nitrate plus nitrite, silica, chloride, and in some cases, orthophosphate and ammonia. All data were recorded continuously on chart recorders, and values were read at frequent time intervals (3-6 min). Maps were produced by superimposing time series of values for each parameter on the cruise track and contouring in appropriate units between the points. The Bayfield nearshore maps were hand contoured, while the Harbor Beach maps were contoured by computer using a geographical mapping program (Cottafava and LeMoli, 1969; as modified by W. Tobler, Univ. of Michigan).

RESULTS

1974 Southern Lake Huron Survey Results

The station locations for the 1974 southern Lake Huron survey cruises are given in Figure 7.1. A comparison of nutrients, chlorophyll *a*, and ^{14}C productivity for inshore and offshore stations on the U.S. and Canadian shores for the first two cruises (Table 7.1) shows high nitrate and total phosphorus along the Canadian shore. The high nutrient levels in the nearshore water appear to have induced large phytoplankton standing crops as evidenced by very high chlorophyll *a* and ^{14}C assimilation values. The phytoplankton assemblage was dominated by diatoms that comprised up to 99 percent of the total assemblage (Tables 7.2, 7.3).

Phytoplankton standing crops and species composition were substantially different in the Ontario nearshore zone as compared with the offshore areas and the Michigan nearshore zone (Tables 7.2, 7.3). Diatom populations characteristic of the offshore spring plankton were *Tabellaria fenestrata*, *Synedra filiformis*, *Fragilaria crotonensis*, *Asterionella formosa*, *Rhizosolenia gracilis*, *Cyclotella stelligera*, *Melosira islandica*, *Fragilaria intermedia* var. *fallax*, and *Stephanodiscus transilvanicus*. These species predominated or were common at all of the offshore stations as well as the nearshore zone on the U.S. shoreline. By comparison, the phytoplankton assemblage during cruise 1 at station 57 on the Canadian shore was dominated by three species of *Stephanodiscus*: *S. hantzschii*, *S. minutus*, and *S. alpinus*, and a population of *Melosira islandica*. *Melosira islandica* was the only species common throughout the lake during the spring but was most abundant in the nearshore samples on the Canadian side of the lake. The *Stephanodiscus* species were routinely observed in the offshore assemblage but were only present in low abundance (<4%).

During the second cruise, nearshore populations on the Canadian shore were again dominated by *Melosira islandica* and *Stephanodiscus* species, with *S. subtilis* replacing *S. alpinus* in the assemblage (Table 7.3), possibly as a result of thermal regime restrictions discussed by Stoermer and Ladewski (1976). As was the case for cruise 1, these populations were not noted in any large abundance at stations near the Michigan shore. Dominance by this group of *Stephanodiscus* species is considered characteristic of enriched habitats in the Great Lakes, particularly parts of Lakes Erie and Ontario (Stoermer and Yang, 1970).

One species, *Fragilaria capucina*, was restricted to the nearshore zone on both sides of the lake. Stoermer and Yang (1970) note that this is primarily a littoral form and that it responds well to added nutrients. The following nearshore periphytic species were also observed at station 57: *Achnanthes lanceolata*, *Fragilaria brevistriata* var. *inflata*, *Fragilaria vaucheriae* var. *truncata*, *Navicula neoventricosa*, *Nitzschia acuta*, *Nitzschia* sp. #2, *Cymbella minuta* var. *silesiaca*, and *Cymbella minuta* f. *latens*. *Meridion circulare* and *Gomphonema olivaceum* were noted at stations 57 and 9; these species originating from tychoplanktonic and epilithic riverine habitats, respectively, are indicative of river influence at these stations.

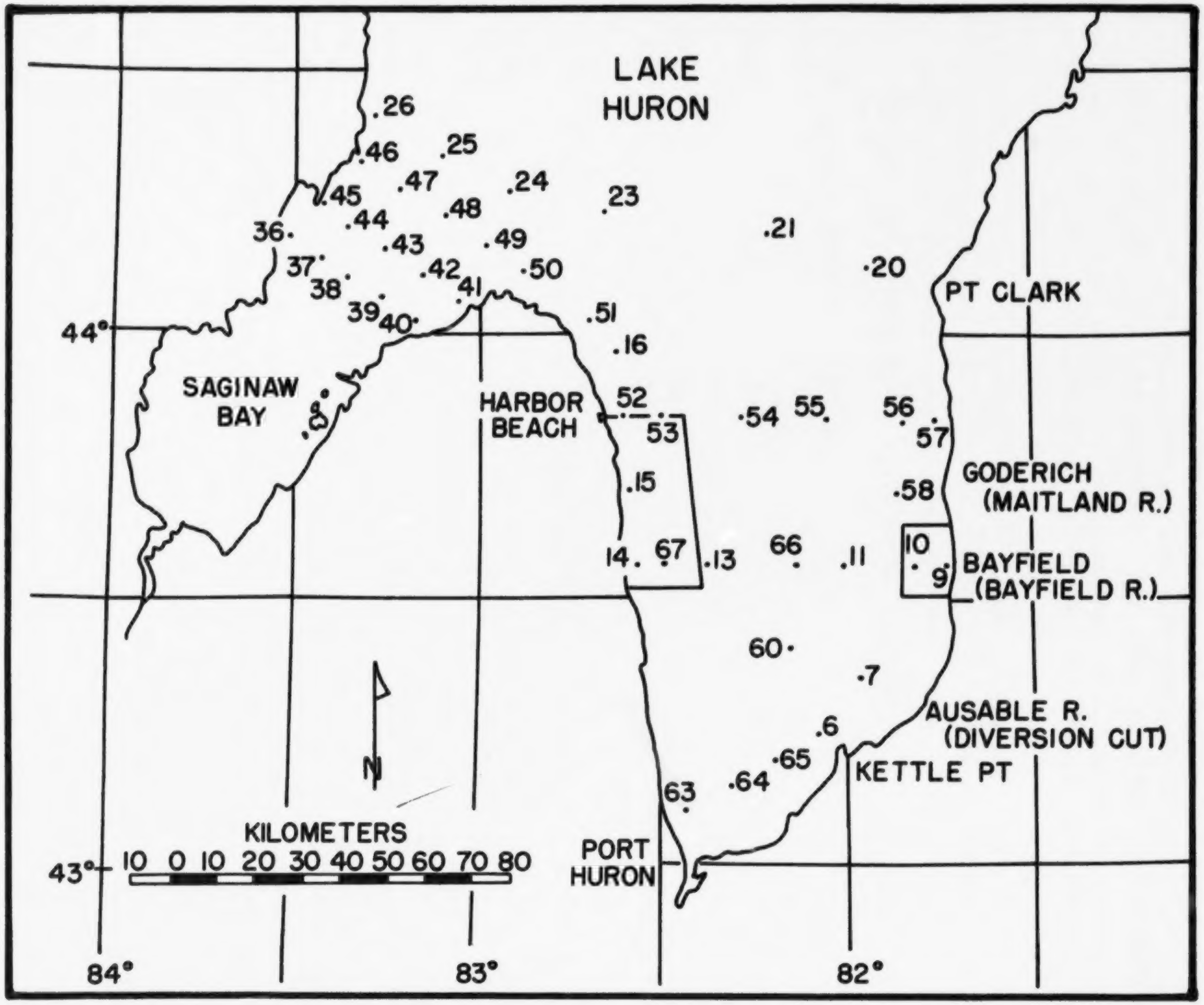

LAKE
HURON
SAGINAW
BAY
HARBOR
BEACH
PORT
HURON
PT CLARK
GODERICH
(MAITLAND R.)
BAYFIELD
(BAYFIELD R.)
AUSABLE R.
(DIVERSION CUT)
KETTLE PT
.26
.46
.25
.45
.47
.24
23
.48
36.
.44
.43
.49
.21
37
38
.42
41
.50
.20
39
40
.51
.16
52
53
.54
55
56
57
.15
.58
14.
67
.13
66
.11
10
9
60
.7
.6
.65
.64
63
N
KILOMETERS
10 0 10 20 30 40 50 60 70 80
44°
43°
84°
83°
82°

Figure 7.1. Station locations for the 1974 southern Lake Huron cruises. Areas studied during the 1975 nearshore cruise are outlined near Bayfield, Ontario, and Harbor Beach, Michigan.

TABLE 7.1. WATER CHEMISTRY AND PHYTOPLANKTON PARAMETERS AT SELECTED STATIONS FOR THE FIRST TWO SOUTHERN LAKE HURON CRUISES, 1974. AVERAGE OF 1 AND 5 METER VALUES

	1974 Station Number	Nitrate µgN/l	Total P µgP/l	Silica $mgSiO_2/l$	Chlorophyll a µg/l	Primary Production mg $C/m^3/hr$
Cruise 1, 28 April to 3 May 1974						
Inshore	57	1331	16.7	1.81	14.8	42.1
Canada	9	-	-	-	-	-
Offshore	56	445	4.2	2.36	3.1	4.5
Canada	10	-	-	-	-	-
Inshore U.S.	14	435	6.4	0.89	5.7	9.4
Offshore U.S.	13	385	3.2	2.70	2.1	3.3
Cruise 2, 14-17 May 1974						
Inshore	57	793	20.4	0.36	13.3	38.6
Canada	9	730	29.5	0.42	8.1	29.5
Offshore	56	356	8.9	0.97	2.7	3.7
Canada	10	385	6.6	0.74	5.4	8.3
Inshore U.S.	14	330	4.1	1.14	3.2	3.7
Offshore U.S.	67	326	3.9	1.50	2.2	3.3

TABLE 7.2. POPULATION ABUNDANCE OF PREDOMINANT DIATOM SPECIES IN SOUTHERN LAKE HURON, CRUISE 1, 28 APRIL-3 MAY 1974

	1974 Station	Total cells/ml	# of species	% Diatoms	Diversity	*M. islandica*	*S. hantzschii*	*S. minutus*	*S. alpinus*	*S. subtilis*	*T. fenestrata*	*F. crotonensis*	*S. filiformis*	*A. formosa*	*F. capucina*	*R. gracilis*	*C. stelligera*
Inshore (Canada)	57 9	2459	53	99	2.449	438(18)	651(24)	199(8)	421(17)	4(0.2)	36(1)	145(6)	67(3)	75(3)	78(3)	36(1)	59(2)
Offshore (Canada)	56 10	1070	41	84	2.995	42(4)	23(2)	44(4)	2(0.2)	9(1)	73(7)	124(11)	149(14)	48(5)	0	65(6)	55(5)
Inshore (U.S.)	14	2649	46	76	2.686	38(1)	52(2)	8(0.3)	4(0.2)	0	247(9)	589(22)	214(8)	48(2)	249(9)	84(3)	13(0.5)
Offshore (U.S.)	13	607	33	83	2.892	27(4)	19(39)	0	2(0.3)	0	25(4)	94(16)	75(12)	84(14)	0	34(6)	31(5)

Cell count densities reported as cells/ml, relative abundance in parenthesis expressed in percentage %.

TABLE 7.3. POPULATION ABUNDANCE OF PREDOMINANT DIATOM SPECIES IN SOUTHERN LAKE HURON, CRUISE 2, 14-17 MAY 1974

	1974 Station	Total cells/ml	# of species	% Diatoms	Diversity	*M. islandica*	*S. hantzschii*	*S. minutus*	*S. alpinus*	*S. subtilis*	*T. fenestrata*	*F. crotonensis*	*S. filiformis*	*A. formosa*	*F. capucina*	*R. gracilis*	*C. stelligera*
Inshore (Canada)	57	2503	64	99	2.837	572(23)	369(15)	337(13)	31(1)	142(6)	90(4)	75(3)	88(4)	128(5)	52(2)	117(5)	73(3)
	9	3008	45	98	2.487	813(27)	253(8)	262(9)	19(1)	92(3)	105(3)	199(7)	62(2)	50(2)	503(17)	63(2)	78(3)
Offshore (Canada)	56	1301	48	84	3.038	52(4)	0	11(1)	15(1)	0	84(6)	168(13)	199(15)	90(7)	0	86(7)	69(5)
	10	1221	43	90	3.038	132(10)	29(2)	23(2)	8(0.7)	0	107(9)	60(5)	136(11)	88(7)	0	65(5)	69(7)
Inshore (U.S.)	14	1405	45	76	2.979	27(2)	19(1)	0	0	0	178(13)	138(10)	147(10)	40(3)	46(3)	126(9)	55(4)
	52	1849	60	74	3.004	36(2)	4(0.2)	4(0.2)	0	0	219(12)	178(10)	170(9)	23(1)	239(13)	132(7)	44(2)
Offshore (U.S.)	67	823	38	80	2.955	21(2)	12(2)	4(1)	8(1)	0	98(12)	25(3)	145(18)	44(5)	21(3)	55(7)	34(4)
	53	528	32	89	2.791	27(5)	4(1)	11(2)	2(0.4)	0	44(8)	0	117(22)	36(7)	0	69(13)	31(6)

Cell count densities reported as cells/ml, relative abundance in parenthesis expressed in percentage %.

High nitrate persisted slightly on the Canadian shore during the third cruise, 4-8 June, 550 μgN/l at stations 9 and 57 in the nearshore as compared with about 400 μgN/l at stations 10 and 56 farther offshore. Values were slightly greaterin the nearshore on the 17-25 June cruise, 420 μgN/l in contrast to 350 μgN/l offshore. These differences in nitrate had disappeared by the 17-24 July cruise.

1975 Nearshore Study

The 29 April to 2 May 1975 cruise focused on the nearshore region around Bayfield, Ontario and on the Michigan shoreline directly across the lake. An east-west transect of stations offshore from Bayfield showed higher nitrate and total phosphorus levels in the nearshore waters (Table 7.4), but nitrate values were not as high as in 1974 (Table 7.1). Nearshore, the chlorophyll a concentration was approximately the same as at the offshore stations, but ^{14}C productivity was twice as high (Table 7.4), indicating a small but very actively growing phytoplankton population in contrast to the large active population observed on the same dates in 1974 (Table 7.1). A major storm passed across southern Lake Huron during the first week of April 1975 and, in general, greatly retarded the spring warming trend. This could easily account for the later development of the spring phytoplankton bloom in 1975 compared with 1974. The silica levels also reflect the lack of diatom growth by the end of April 1975; the silica levels nearshore are still slightly higher than the offshore values. This indicates that there was a minor source of silica in the nearshore, either regeneration from the sediments or runoff.

Underway maps of temperature, nitrate, silica and chloride were also made on 30 April 1975 (Figures 7.2a, b, c, d). South-southeast winds of 20-24 knots prevailed for 24 hr preceding and during the mapping run. As a consequence, water from the Bayfield River appears to have been transported north along the Ontario shore. This is clearly indicated by the temperature and chloride distribution and indicates that the high nitrate and silica values observed at the northern nearshore turn can also be attributed to the Bayfield River plume. The middle nearshore turn, which is 0.7 km offshore and 0.7 km south of the river mouth, apparently missed most of the river plume that was close to the shore moving north under the prevailing winds.

As a check that the observed plume north of the river mouth was indeed Bayfield River water, a comparison was made between the river water and the observed enrichment of the nearshore waters for chloride and nitrate. These are the only parameters that were measured in both the underway maps and the Ontario Ministry of the Environment (1978) river studies (data of 22 April 1975). The center of the observed plume was calculated to be 10 percent and 12 percent river water based on chloride and nitrate concentrations, respectively. The excellent agreement of these numbers is a clear indication that the observed plume was Bayfield River water. In addition, water with temperatures greater than 6°C that flowed north also had enriched silica concentrations.

The nitrate and to some extent the chloride distribution also showed high concentrations south of Bayfield. This indicates that either the river

TABLE 7.4. AVERAGE VALUES FOR THE UPPER 10 m ALONG A TRANSECT DUE WEST OF BAYFIELD, ONTARIO, 30 APRIL 1975

Station	Km from shore	T°C	Nitrate μgN/l	Total P μgP/l	Silica mgSiO$_2$/l	Chlorophyll a μg/l	Primary Production mg C/m^3/hr
N11	1	5.1	636	29.7	1.37	1.0	4.3
N12	7.5	3.1	359	12.5	1.27	1.2	2.5
N13	13	3.1	353	11.1	1.27	1.1	2.5

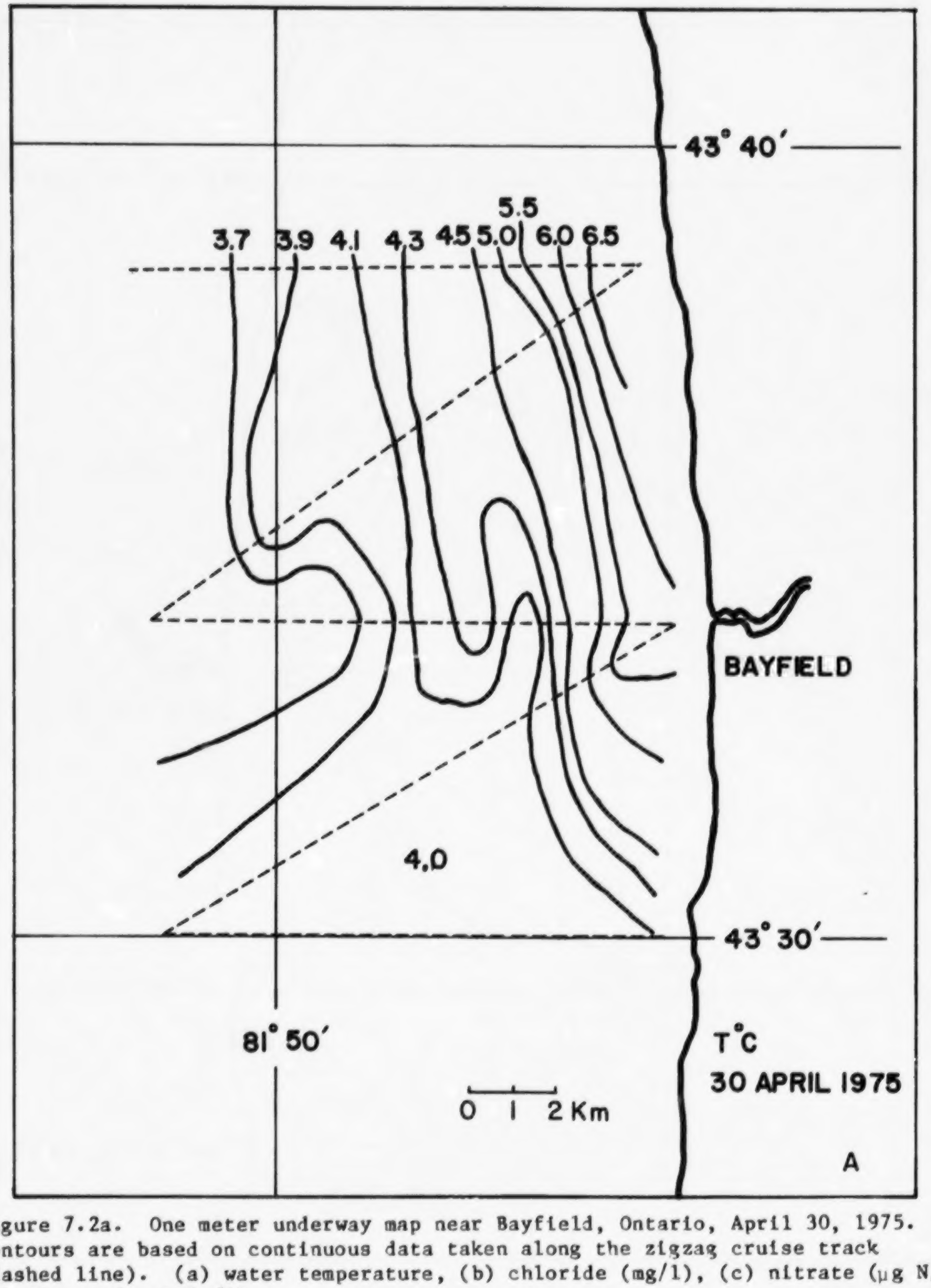
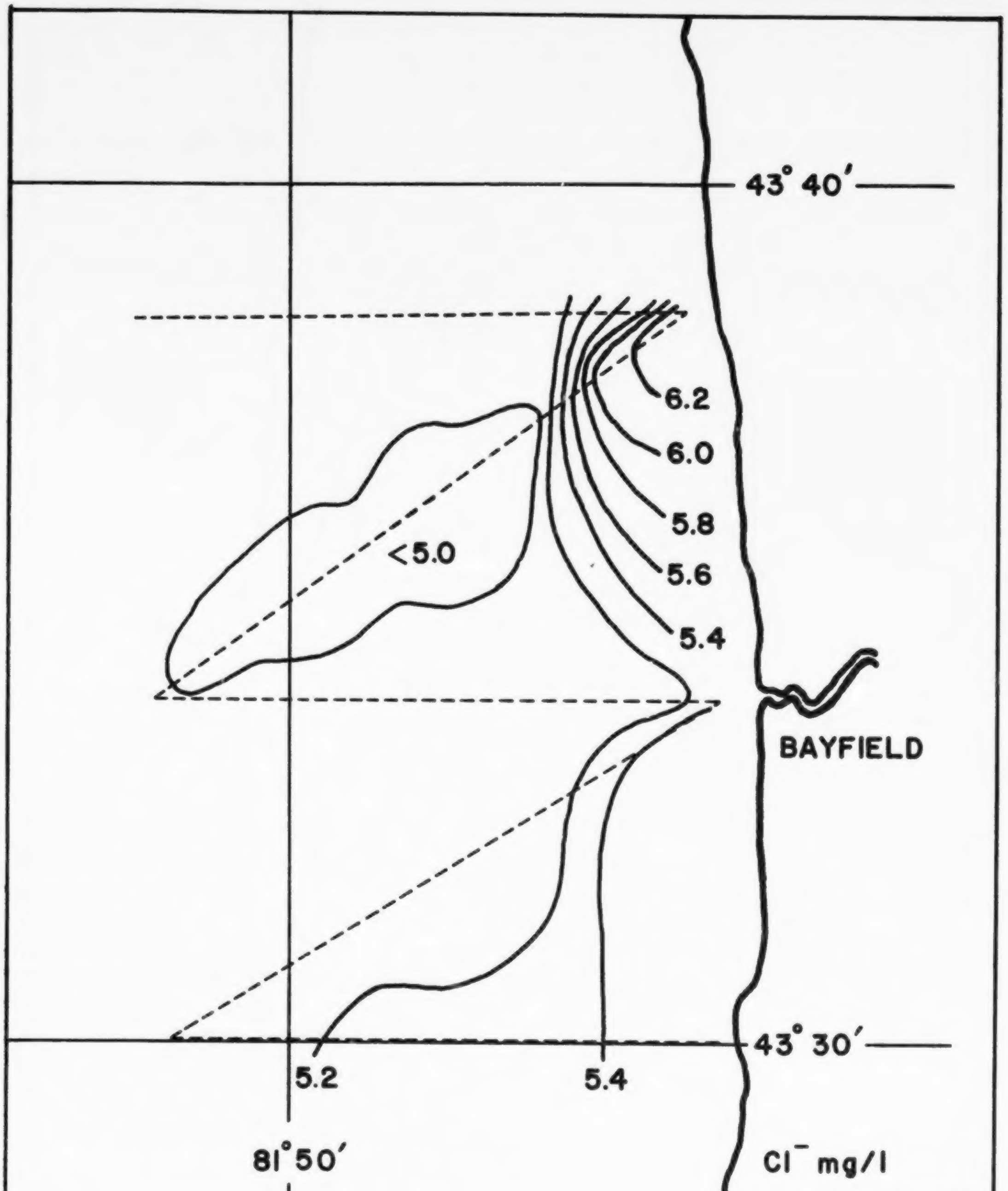

43° 40′
5.5
3.7
3.9
4.1
4.3
4.5
5.0
6.0
6.5
BAYFIELD
4.0
43° 30′
81° 50′
T°C
30 APRIL 1975
0 1 2 Km
A

Figure 7.2a. One meter underway map near Bayfield, Ontario, April 30, 1975. Contours are based on continuous data taken along the zigzag cruise track (dashed line). (a) water temperature, (b) chloride (mg/l), (c) nitrate (μg N/l), (d) silica (mg SiO_2/l).



43° 40′
6.2
6.0
5.8
<5.0
5.6
5.4
BAYFIELD
43° 30′
5.2
5.4
81° 50′
Cl⁻ mg/l
30 APRIL 1975
B

Figure 7.2b. One meter underway map of chloride (mg/l) near Bayfield, Ontario, 30 April 1975. See Figure 7.2 for more details.

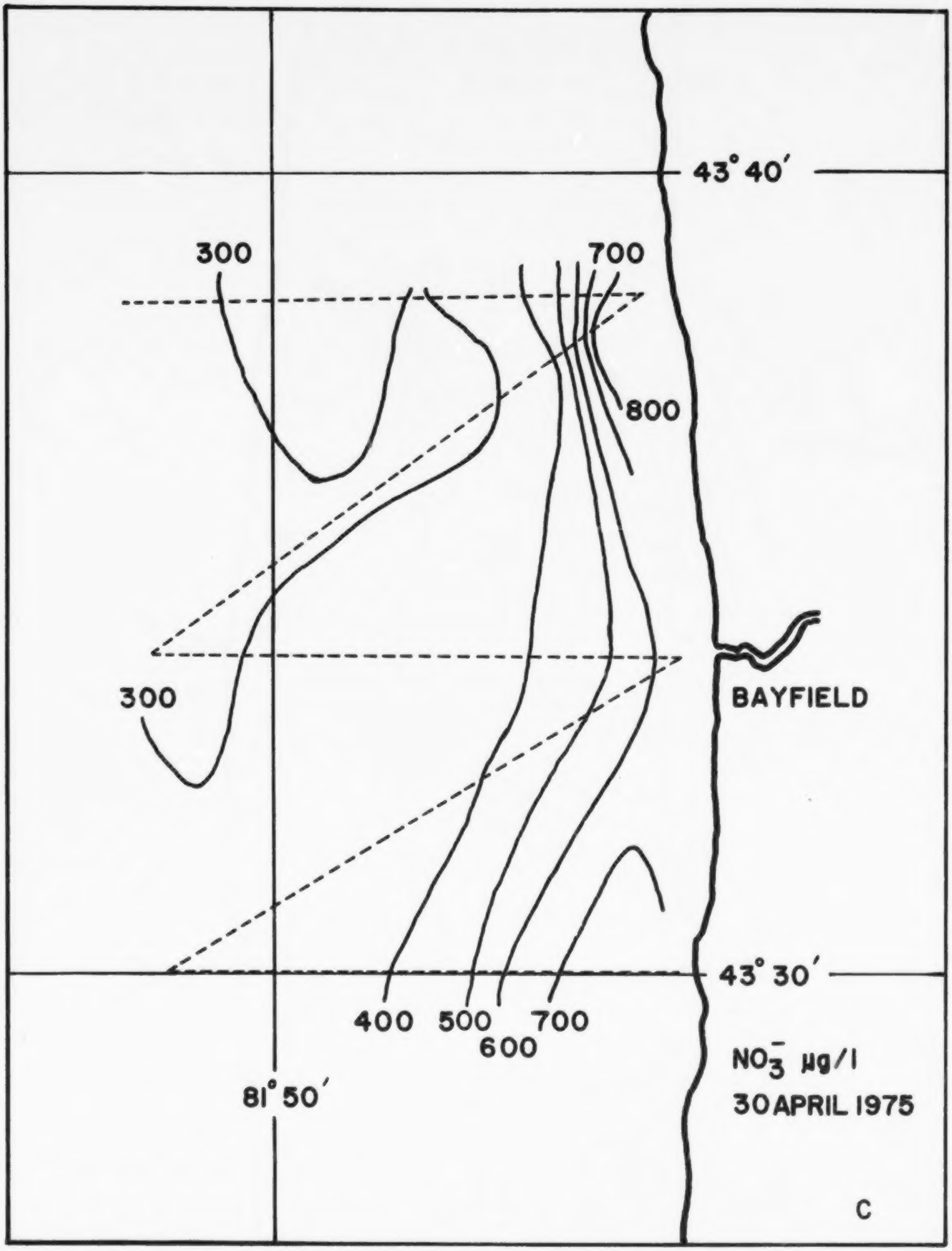

43° 40′
300
700
800
BAYFIELD
300
43° 30′
400
500
600
700
NO$_3^-$ µg/l
30 APRIL 1975
81° 50′
C

Figure 7.2c. One meter underway map of nitrate (µgN/1) near Bayfield, Ontario, 30 April 1975. See Figure 7.2 for more details.

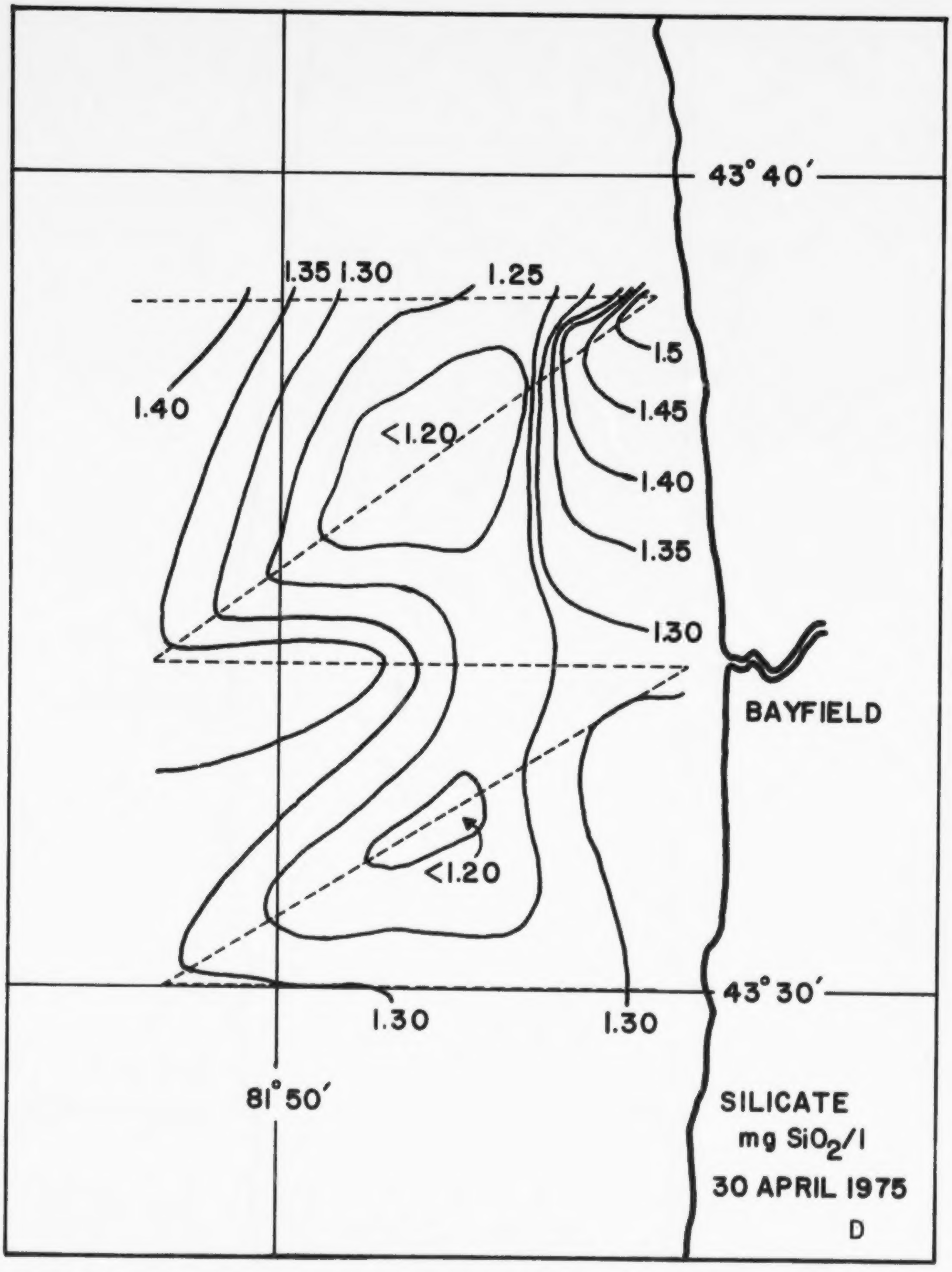

43° 40′
1.35
1.30
1.25
1.40
1.5
1.45
<1.20
1.40
1.35
1.30
BAYFIELD
<1.20
43° 30′
1.30
1.30
81° 50′
SILICATE
mg SiO_2/l
30 APRIL 1975
D

Figure 7.2d. One meter underway map of silica (mg SiO_2/l) near Bayfield, Ontario, 30 April 1975. See Figure 7.2 for more details.

plume was recently transported south along the shore under west or northwest winds or that there is another nutrient source south of Bayfield and that water from that source has been transported north along the coast.

A band of lower silica inside the 4°C isotherm (thermal bar) on the Bayfield transect indicates that a diatom bloom is beginning to develop in the nearshore waters (Fig. 7.2d). This is the area that had the very large phytoplankton bloom in April-May 1974, but the bloom was not yet well developed by 1 May 75. Stoermer (1968) found the largest phytoplankton populations just inside the thermal bar. This may result, in part, from physical processes because the thermal bar is a region of downwelling, and nearshore surface waters move offshore to the bar and sink, tending to concentrate material there (Rodgers, 1965).

In contrast, on the Michigan shore, even though the thermal bar was present (Figure 7.3a), high nitrate levels were not observed in the underway map of the nearshore waters (Figure 7.3c). The nitrate distribution was fairly uniform with a total variation of only 20 percent over the entire map as compared with the three times higher values found nearshore on the Ontario side. On the Michigan shore, the lowest nitrate values were found close to shore, probably reflecting the phytoplankton growth inshore of the thermal bar that is also indicated by the chlorophyll distribution (Figure 7.3e). Silica levels are also reduced inshore reflecting diatom growth (Figure 7.3d). The highest chloride values were found inshore of the thermal bar (Figure 7.3b), indicating some minor source of runoff or cultural inputs along the Michigan shore. Possibly this was material transported south along the shore from Saginaw Bay that has a high chloride content (Ayers et al., 1956; Section 3).

The Michigan shore underway maps were made during a calm period following two days of SSE winds at 20-24 knots. The wind reversed on the evening of 1 May 1975 to WNW at 10-15 knots. Temperature profiles were made on an east-west transect of eight stations on 2 May (Figure 7.4), which shows that the thermal bar had moved 5 km inshore under the new wind regime. The temperature profiles depict the classic thermal bar situation with reverse thermal stratification offshore of the 4°C water and a positive thermocline established on the inshore side. The station data indicate that the surface distributions observed in the underway maps were consistent with depth. At five of the stations, water samples were taken for chloride, silica, chlorophyll $\underline{a}$, and nitrate profiles (Figure 7.5a, b, d, c). Chloride was highest inshore. Chlorophyll $\underline{a}$ was also greater inshore, indicating the beginning of a phytoplankton bloom in the recently stabilized waters. Silica was reduced in the nearshore waters, reflecting phytoplankton growth, whereas the nitrate distribution was relatively uniform, probably reflecting a balance between consumption by phytoplankton and a minor source(s) along the shore.

DISCUSSION

The Great Lakes have a persistent year-round coastal boundary layer (CBL), defined as a band of water approximately 10 km wide, which is

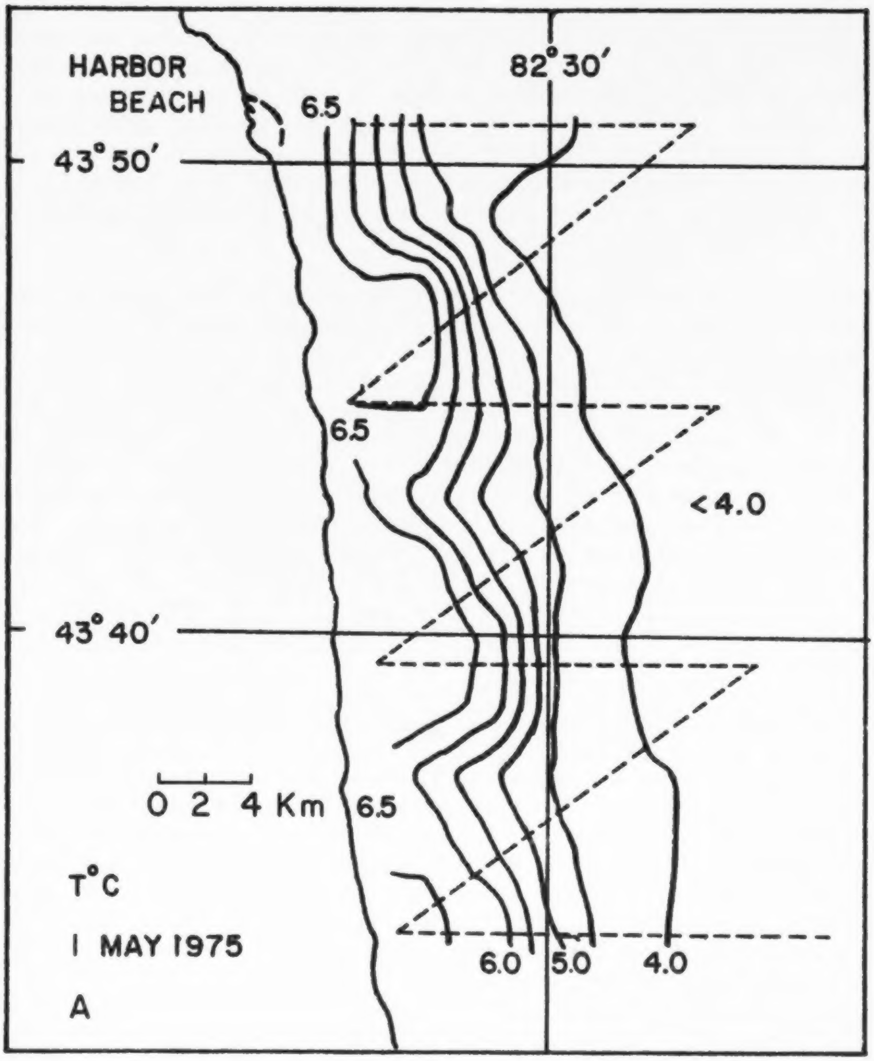

HARBOR BEACH
82°30′
6.5
43°50′
6.5
<4.0
43°40′
0 2 4 Km
6.5
T°C
1 MAY 1975
A
6.0
5.0
4.0

Figure 7.3a. One meter underway map near Harbor Beach, Michigan, 1 May 1975. Dashed line is the cruise track. (a) water temperature, (b) chloride (mg/l), (c) nitrate (μg N/l), (d) silica (mg SiO_2/l), (e) chlorophyll fluorescence: 7 units $\approx$ 1 μg Chl a/l.

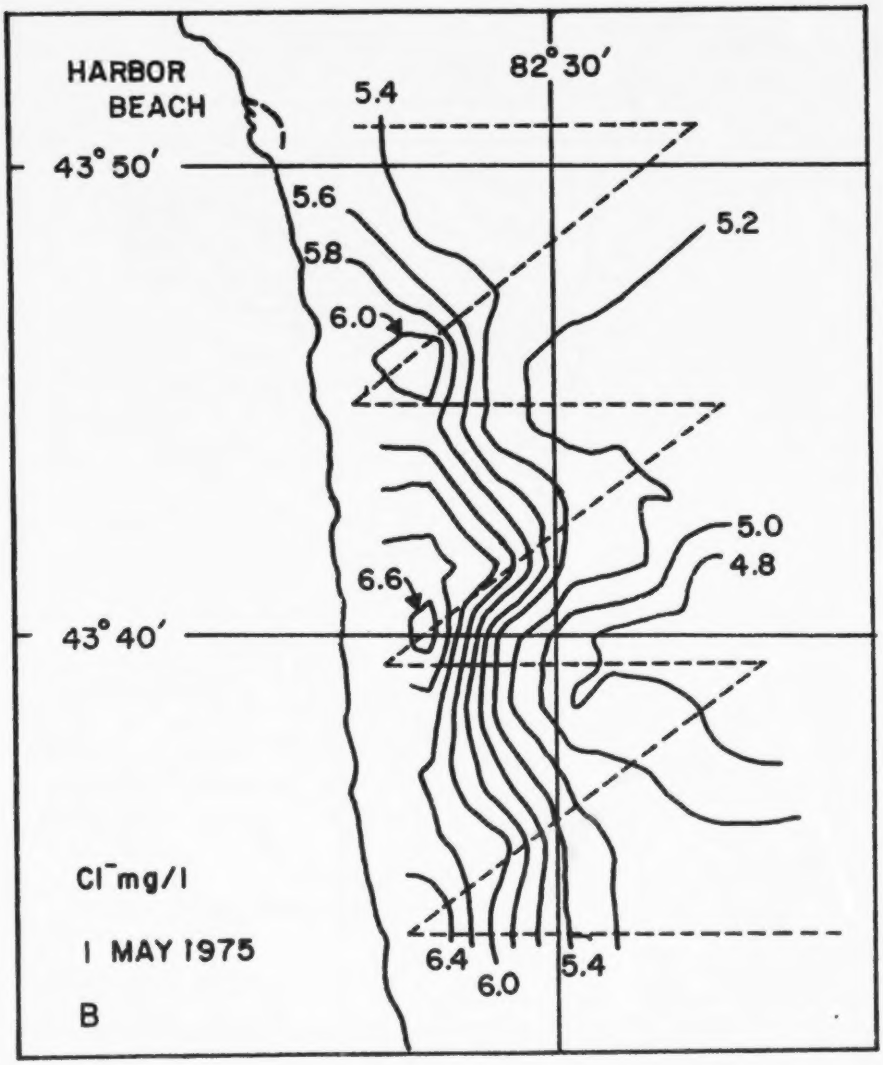

HARBOR BEACH
82°30′
5.4
43°50′
5.6
5.2
5.8
6.0
5.0
4.8
6.6
43°40′
Cl⁻mg/l
1 MAY 1975
6.4
6.0
5.4
B

Figure 7.3b. One meter underway map of chloride (mg/l) near Harbor Beach, Michigan, 1 May 1975. See Figure 7.3 for more details.

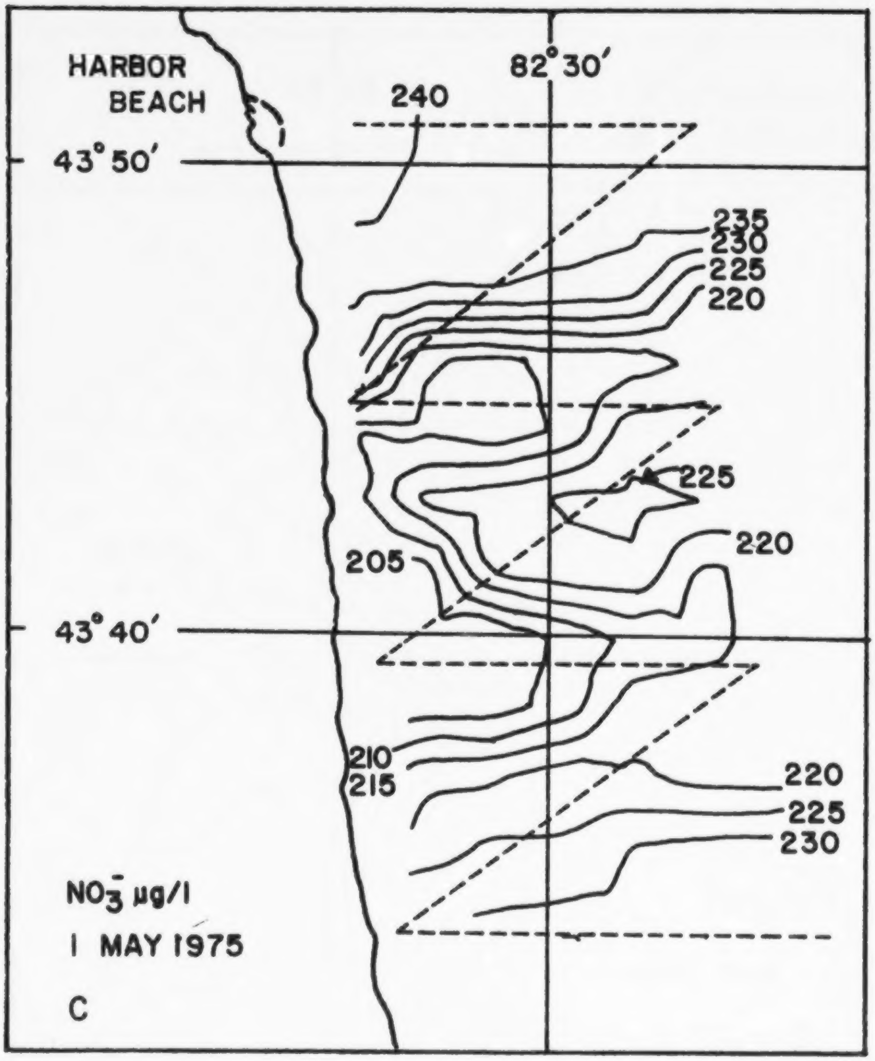

HARBOR BEACH
82°30′
240
43°50′
235
230
225
220
225
220
205
43°40′
210
215
220
225
230
NO$_3^-$ µg/l
1 MAY 1975
C

Figure 7.3c. One meter underway map of nitrate (µgN/1) near Harbor Beach, Michigan, 1 May 1975. See Figure 7.3 for more details.

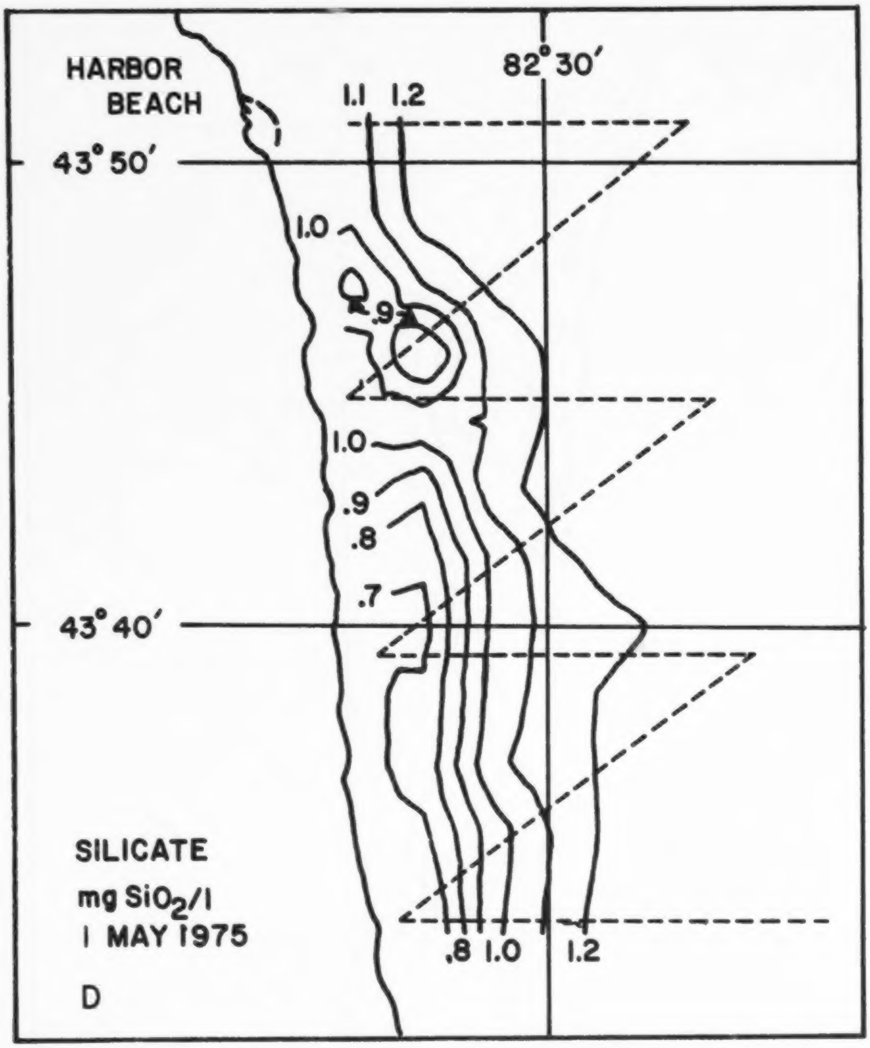

HARBOR BEACH
82°30′
43°50′
43°40′
1.1
1.2
1.0
.9
1.0
.9
.8
.7
.8
1.0
1.2
SILICATE
mg SiO2/l
1 MAY 1975
D

Figure 7.3d. One meter underway map of silica (mg SiO_2/l) near Harbor Beach, Michigan, 1 May 1975. See Figure 7.3 for more details.

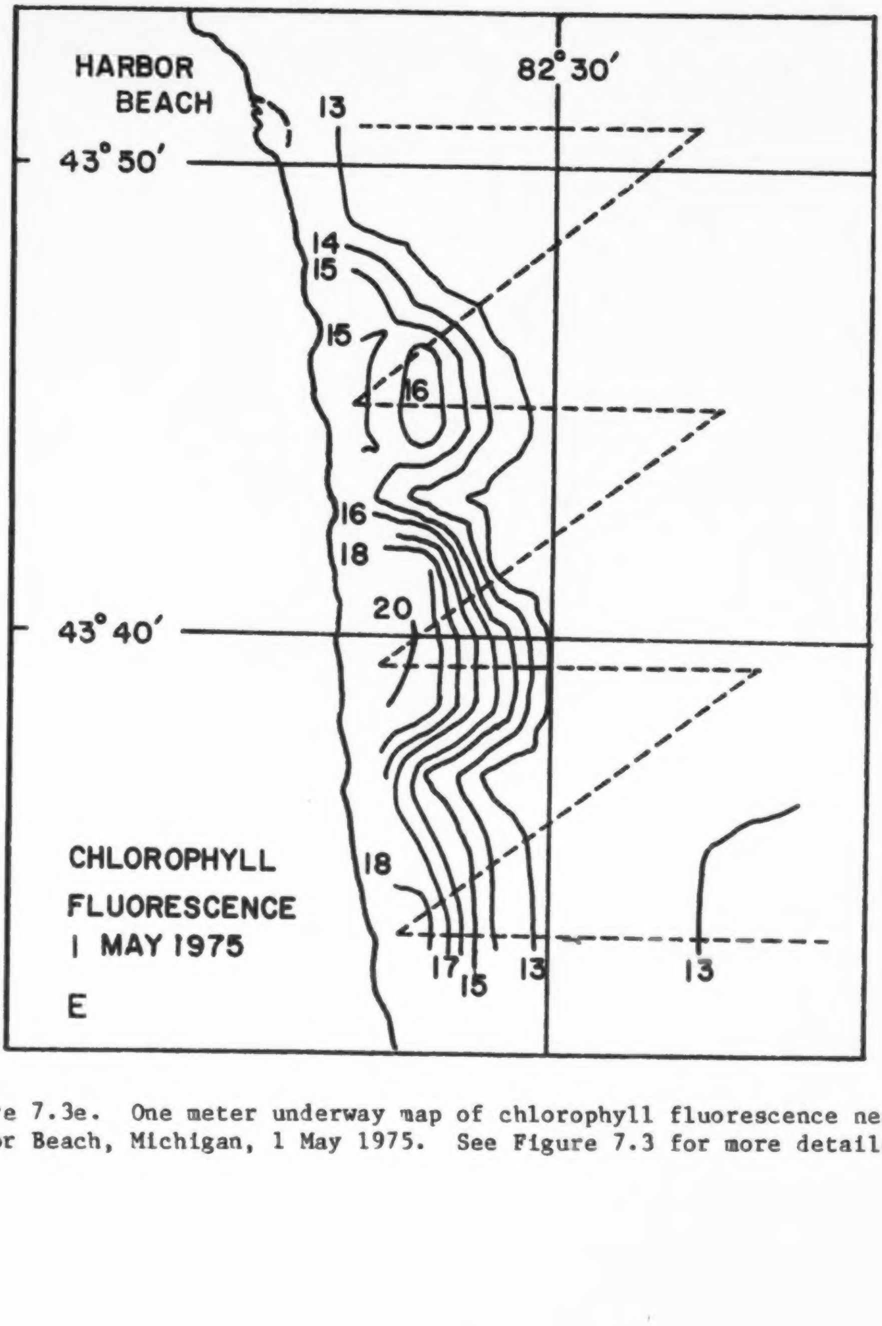

HARBOR BEACH
82°30′
43°50′
43°40′
13
14
15
15
16
16
18
18
20
18
17
15
13
13
CHLOROPHYLL FLUORESCENCE
1 MAY 1975
E

Figure 7.3e. One meter underway map of chlorophyll fluorescence near Harbor Beach, Michigan, 1 May 1975. See Figure 7.3 for more details.

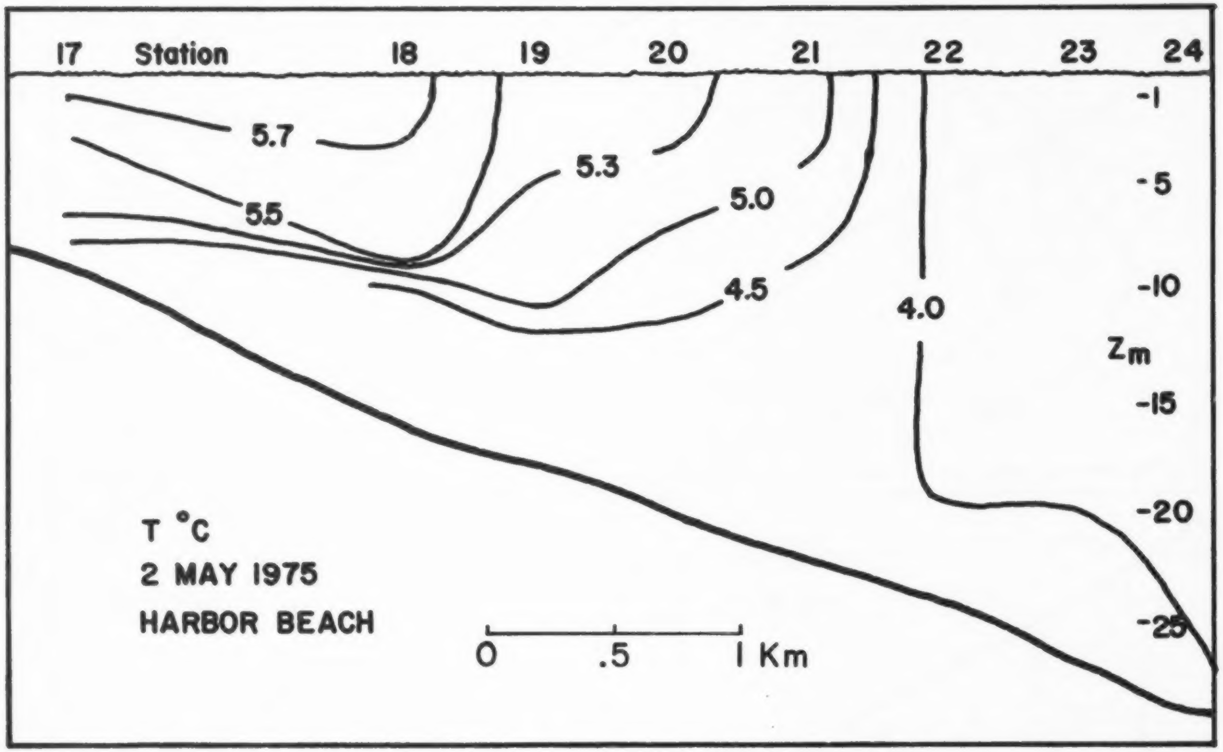


Figure 7.4. Temperature distribution at 8 stations on a 5 km east-west transect 10.5 km south of Harbor Beach, Michigan.

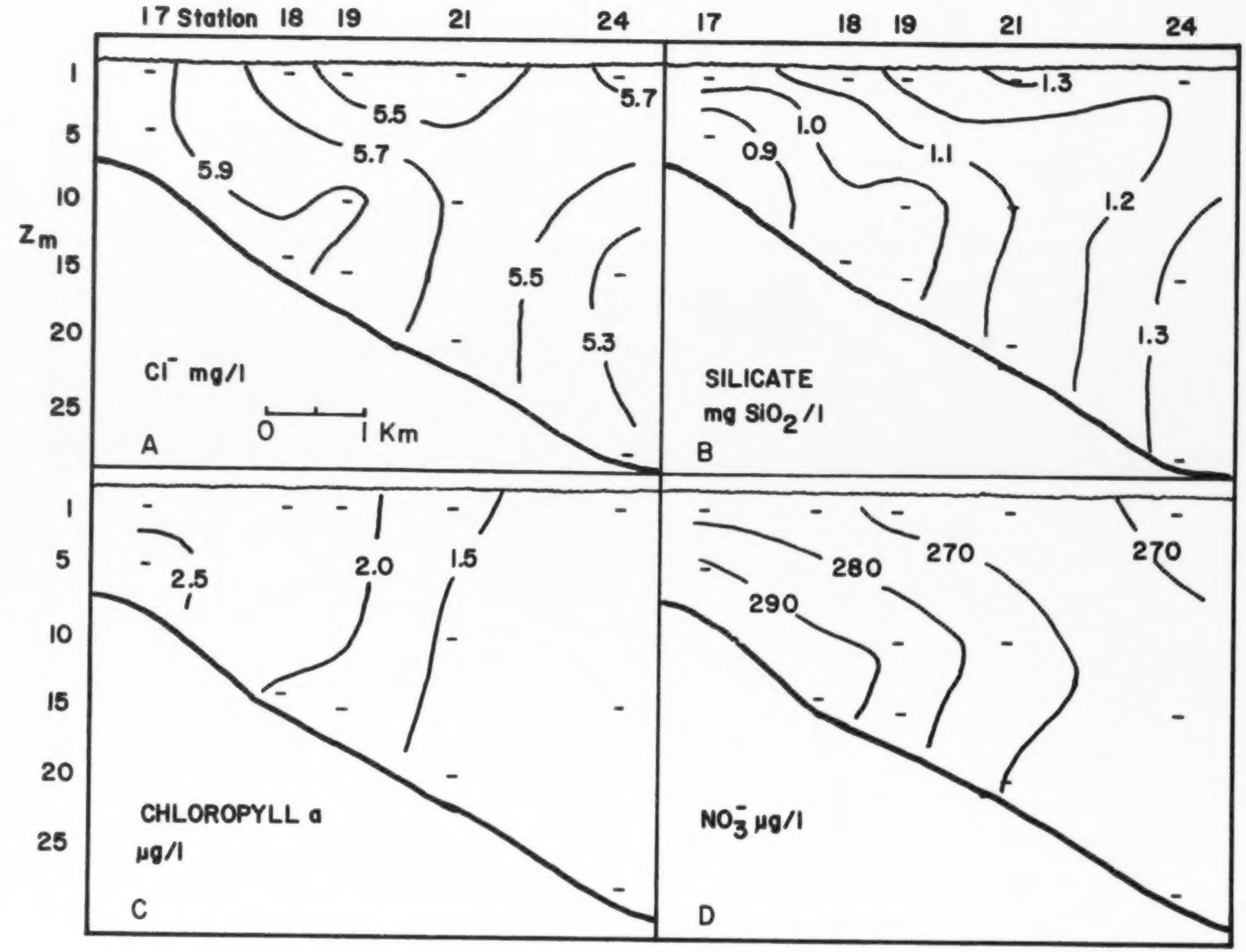


Figure 7.5. Chemical parameters and chlorophyll a at selected stations along the transect. (a) chloride (mg/l), (b) silica (mg SiO_2/l), (c) chlorophyll a (µg/l), (d) nitrate (µg N/l).

dominated by a relatively persistent longshore flow (Csanady, 1975). This feature serves to trap runoff and domestic inputs from the shore in a narrow nearshore zone representing perhaps only 1 percent of the water volume of the lakes. Thus, materials dumped into the lake continue to be a problem until physical processes, which at this time are poorly understood, mix the material from the CBL to the midlake water mass (Csanady, 1975). The nutrient concentrations in the Great Lakes rivers are closely tied to flow rate, with the highest concentrations being found at times of high runoff (Ontario Ministry of Environment, 1978; Stephenson and Waybrant, 1971). Rivers, during winter and spring, therefore may carry a majority of their nutrient load to the lake; for example, from January to April, and in December 1975, the Maitland River carried 88 percent of its total annual nitrate nitrogen load (Ontario Ministry of Environment, 1978). Compounding the problem is the presence of the thermal bar that effectively prevents the mixing of the nutrient-rich water from the CBL to the open lake during the spring. The results of our study confirm this phenomenon, showing that the nutrients carried by the Bayfield River are retained inside the thermal bar.

Calculations based on the Ontario Ministry of Environment (1978) data for the Maitland, Ausable, and Bayfield rivers suggest that these rivers may account for most of the excess nitrate found in the nearshore zone from Point Clark to Kettle Point. Assuming a nearshore zone of 100 km x 5 km (the distance offshore to the thermal bar 30 April 1975) x 10 m deep, the nitrate carried by the rivers in April 1975 was sufficient to add approximately 260 μgN/l to the entire nearshore. Added to the open lake background of 350 μgN/l this gives an average of 620 μgN/l which can be compared to the observed value near Bayfield of 640 μgN/l (Table 7.4). This rough calculation suggests that most of the enrichment of the nearshore zone observed in late April 1975 was derived from river inputs.

Samples from the 1974 spring cruises indicate that the large phytoplankton bloom based on river-borne nutrients developed nearshore after the thermal bar formed. In 1974, this large spring bloom resulted in silica depletion to 0.4 mg/l SiO_2 by 15 May (Table 7.1) even though, as is indicated in Figure 7.2d, a significant amount of silica was also being carried by the Bayfield River. Further silica depletion could limit the growth of diatoms and favor a change to blue-green and green algae (Schelske and Stoermer, 1971, 1972). Although the thermal bar is present only during spring in southern Lake Huron, the CBL persists throughout the summer and is reasonably effective at preventing mixing between nearshore and offshore waters. For example, Holland and Beeton (1972) found that unique phytoplankton populations were maintained year round in the nearshore zone in Lake Michigan, which had a different species composition and higher total numbers than the offshore populations. Conditions that develop in the nearshore zone and lead to a bloom of diatoms or possibly blue-green and green algae may be relatively independent of conditions in the offshore waters. The presence of the thermal bar at the time of spring runoff may thus play a crucial role in the early development of nuisance algal blooms in nearshore regions.

The impact of river-borne nutrients on the nearshore zone of Lake Huron varies greatly with season as a function of river flow, associated nutrient concentrations, and the presence of the thermal bar. River flow is highest in December to April averaging 100 times the flow in July to September in normal years. Nutrient concentration of river water varies, being roughly proportional to flow rate, with the winter values being roughly 10 times the late summer values in normal years. Daily inputs of nutrients, therefore, are often 1,000 times higher in the winter compared to typical summer loadings. However, if as in 1975, August and September are particularly wet, the rivers maintain high flow rates and high nutrient levels and the nutrient load per day to the lakes will be 100 times higher than normal (Ontario Ministry of Environment, 1978). In moderate to high flow situations, the nutrients are carried directly into the lake unchanged, while in low flow situations phytoplankton and macrophytes in the river deplete nutrients to very low levels, often to levels less than surface values in the lake.

River-borne nutrients have the largest effect on the nearshore zone in April when the river flow and nutrient levels are high and when the thermal bar retains the nutrients in the nearshore zone. In addition, the river water is generally warmer than the nearshore lake water at this time, and consequently the river water may float as a surface layer inside the thermal bar. During the nearshore cruise (Figure 7.2a), the thermal bar was only 5 km offshore, and the Bayfield River water was 9°C while the nearshore water was <6°C. The input of warmer river water increases the temperature and thermal stability of the water column inshore from the thermal bar and provides nutrients to the surface layer, all of which are instrumental in developing large early spring phytoplankton blooms in the nearshore zone.

Clearly, April through May, the period of the thermal bar, is the time of year when river-borne nutrients should have maximum effect on water quality in the nearshore zone in southern Lake Huron. In 1975, the 29 April to 2 May cruise was too early for the spring phytoplankton bloom in the nearshore zone; however, in 1974 survey data showed a large bloom developing in April and May in the nearshore zone influenced by the Maitland and Bayfield Rivers. The 1974 bloom was primarily composed of Stephanodiscus species that typically bloom only in nutrient enriched areas (Stoermer and Yang, 1970).

Comparing Michigan and Ontario nearshore regions of southern Lake Huron points to the important role of the nearshore zone as an extension of the rivers, particularly during the thermal bar period. On the Ontario shore, the Bayfield, Maitland, and Ausable Rivers drain large areas of primarily agricultural lands, resulting in high nutrient loading in the nearshore zone, particularly during spring runoff, and this apparently causes large spring blooms such as those observed in 1974 (Table 7.1). At the same latitude, the Michigan nearshore receives only local runoff, and does not exhibit elevated nitrate levels or a particularly intense spring bloom. On the Michigan coast, the majority of the region's runoff enters Saginaw Bay via the Saginaw River. Saginaw Bay, being highly eutrophic, processes these nutrients so that little of this material reaches the open lake.

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APPENDIX A.

Average wind direction and speed at Selfridge AFB,
latitude 42° 36' N, longitude 82° 50' W.
(Wind speed is given in knots)

Month: January

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	not avail.	not avail.	16	26.4	8.1
2	20.3	2.9	17	5.8	9.0
3	32.9	4.6	18	8.9	4.1
4	25.8	4.7	19	3.6	6.3
5	not avail.	not avail.	20	12.3	6.6
6	not avail.	not avail.	21	22.8	10.9
7	25.4	11.1	22	17.8	3.9
8	13.7	5.0	23	26.9	9.3
9	1.4	6.7	24	23.2	8.0
10	2.4	5.2	25	22.5	8.5
11	33.9	6.1	26	16.4	7.6
12	28.8	5.9	27	25.5	16.5
13	19.2	6.2	28	2.3	3.0
14	20.9	10.6	29	21.9	5.7
15	25.3	9.6	30	21.0	12.3
			31	25.9	16.6

Month: February

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	2.3	8.6	16	26.9	5.3
2	5.1	13.3	17	31.7	6.9
3	3.6	5.0	18	14.6	9.6
4	1.0	7.0	19	7.0	6.5
5	5.8	5.8	20	26.0	5.0
6	5.1	12.3	21	9.2	4.1
7	34.3	9.8	22	20.2	14.4
8	30.1	3.3	23	30.8	13.6
9	27.0	5.9	24	1.8	8.6
10	23.5	12.0	25	31.0	8.8
11	24.1	11.3	26	24.4	6.9
12	18.3	4.4	27	20.7	9.8
13	25.8	6.4	28	23.5	11.9
14	1.9	10.6			
15	2.8	3.3			

(continued).

APPENDIX A. (continued).

Month: March

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	23.1	6.9	16	33.1	7.2
2	14.3	3.2	17	30.7	13.5
3	19.0	12.9	18	24.3	8.5
4	17.5	6.2	19	33.0	8.6
5	26.5	9.7	20	6.8	3.5
6	18.0	6.8	21	34.0	8.8
7	30.9	6.6	22	24.2	11.7
8	7.0	9.6	23	29.6	8.7
9	11.4	4.0	24	28.8	10.9
10	0.6	9.4	25	21.0	8.3
11	10.0	4.3	26	28.0	12.4
12	4.3	11.2	27	6.7	1.1
13	35.3	9.2	28	8.1	9.2
14	22.4	4.5	29	8.3	9.6
15	12.4	7.9	30	5.8	7.2
			31	31.9	9.3

Month: April

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	9.1	7.1	16	27.0	3.5
2	23.0	9.5	17	28.3	6.7
3	13.9	7.2	18	33.5	7.6
4	22.0	12.4	19	5.0	7.2
5	30.8	8.0	20	12.4	5.5
6	28.8	7.0	21	21.5	10.2
7	33.8	9.1	22	24.3	10.6
8	2.7	10.3	23	31.6	11.6
9	2.0	10.2	24	0.3	11.0
10	20.8	4.7	25	24.3	4.8
11	13.6	3.1	26	13.0	1.2
12	17.1	9.7	27	17.3	4.8
13	24.0	11.5	28	22.7	6.9
14	22.6	15.6	29	25.0	7.1
15	32.1	11.7	30	26.7	6.1

(continued).

APPENDIX A. (continued).

Month: May

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	36.0	8.0	16	9.8	5.9
2	11.0	5.6	17	28.9	5.0
3	27.4	4.7	18	3.0	5.4
4	10.2	3.8	19	5.0	7.3
5	18.0	7.9	20	11.3	5.0
6	32.4	8.9	21	11.3	1.7
7	27.5	4.0	22	28.2	4.6
8	10.4	10.0	23	26.2	7.7
9	35.4	7.1	24	28.3	8.7
10	21.0	4.5	25	30.0	5.8
11	16.5	7.6	26	34.6	3.8
12	22.9	8.1	27	17.8	2.3
13	34.6	8.8	28	18.3	4.8
14	21.5	12.3	29	33.3	4.1
15	27.6	11.0	30	3.5	5.0
			31	26.1	8.3

Month: June

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	16.3	2.5	16	26.1	5.7
2	14.5	2.0	17	23.8	5.9
3	15.0	1.4	18	22.4	3.5
4	20.7	6.3	19	17.3	2.7
5	16.8	6.2	20	18.2	3.3
6	16.1	7.4	21	24.5	6.3
7	16.7	10.8	22	1.0	5.5
8	19.5	6.8	23	0.7	9.9
9	19.6	7.5	24	35.8	6.5
10	23.0	11.4	25	0.8	5.3
11	27.3	7.6	26	3.4	5.0
12	26.7	5.7	27	13.0	3.0
13	19.1	6.1	28	14.5	2.3
14	19.5	8.3	29	23.5	3.3
15	19.6	5.9	30	26.5	10.5

(continued).

APPENDIX A. (continued).

Month: July

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	24.3	6.3	16	7.0	1.8
2	23.3	9.1	17	15.2	5.7
3	22.8	8.7	18	24.2	10.5
4	23.3	9.7	19	25.3	6.8
5	31.8	5.2	20	4.4	7.0
6	8.8	2.8	21	14.8	3.5
7	14.8	2.8	22	5.9	5.0
8	20.7	1.7	23	4.7	5.5
9	26.3	5.3	24	4.3	2.0
10	2.3	7.8	25	14.0	2.1
11	4.2	8.8	26	13.6	3.0
12	9.0	2.7	27	28.0	4.9
13	23.8	3.7	28	23.6	4.2
14	23.3	5.5	29	26.7	6.0
15	0.2	8.2	30	26.7	7.0
			31	27.5	5.7

Month: August

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	23.6	3.9	16	19.0	4.0
2	13.3	4.4	17	29.7	5.7
3	20.8	7.5	18	25.7	3.2
4	24.7	9.3	19	22.5	1.3
5	32.3	5.7	20	16.0	2.9
6	19.0	3.2	21	16.5	4.5
7	12.8	2.4	22	18.3	3.7
8	2.1	4.0	23	31.8	4.4
9	0.6	3.4	24	35.2	4.0
10	10.3	6.3	25	6.8	2.3
11	16.6	9.4	26	20.0	5.3
12	25.5	4.8	27	29.8	5.0
13	33.6	5.6	28	3.5	3.2
14	4.6	4.8	29	9.2	3.0
15	10.6	4.0	30	17.7	2.7
			31	27.1	7.3

(continued).

APPENDIX A. (continued).

Month: September

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	34.8	2.5	16	6.0	2.3
2	3.5	6.9	17	27.8	7.1
3	1.9	4.8	18	4.4	4.4
4	2.8	3.3	19	19.4	6.0
5	8.5	2.5	20	34.8	5.4
6	10.0	1.8	21	31.3	4.3
7	13.5	1.3	22	35.0	9.4
8	22.8	3.1	23	21.5	3.0
9	23.0	3.9	24	19.0	7.8
10	21.4	3.5	25	25.7	7.3
11	21.7	8.1	26	24.5	5.8
12	23.9	5.8	27	19.3	6.8
13	28.3	9.1	28	18.5	6.6
14	26.8	5.7	29	26.4	8.6
15	27.3	9.3	30	28.8	5.5

Month: October

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	29.8	9.4	16	21.0	1.6
2	32.7	9.2	17	28.0	10.8
3	22.6	4.3	18	1.0	5.0
4	19.7	7.1	19	33.8	5.5
5	22.0	9.8	20	1.0	5.4
6	23.3	9.8	21	22.3	5.7
7	31.6	7.0	22	22.3	10.7
8	20.5	4.7	23	1.0	2.2
9	28.3	3.1	24	20.0	3.3
10	26.7	2.6	25	29.4	7.6
11	18.8	3.7	26	27.0	5.5
12	31.4	6.0	27	22.3	3.5
13	10.6	6.4	28	17.5	1.5
14	23.1	10.2	29	16.4	3.5
15	29.2	6.2	30	20.9	8.0
			31	19.5	6.9

(continued).

APPENDIX A. (continued).

Month: November

Date	Avg. Wind Direction	Avg. Wind Speed
1	23.4	7.1
2	8.8	4.1
3	22.1	8.0
4	0.7	7.3
5	0.5	10.3
6	31.1	5.3
7	26.3	2.0
8	21.0	2.8
9	15.5	1.8
10	13.3	4.7
11	19.7	9.8
12	29.4	6.7
13	25.6	9.3
14	26.7	11.6
15	23.0	14.0
16	21.5	8.2
17	21.7	8.3
18	21.3	5.9
19	18.9	4.7
20	27.6	8.3
21	32.6	14.1
22	24.7	4.9
23	18.7	8.9
24	28.1	12.1
25	33.9	9.8
26	6.7	4.0
27	19.0	7.7
28	26.9	7.6
29	33.8	4.2
30	6.7	12.0

Month: December

Date	Avg. Wind Direction	Avg. Wind Speed
1	5.4	16.3
2	1.1	16.1
3	32.6	12.1
4	28.5	5.7
5	23.0	2.7
6	20.2	5.1
7	16.9	4.0
8	28.9	9.4
9	30.1	9.9
10	22.7	7.7
11	20.3	4.4
12	26.6	2.4
13	8.0	2.1
14	3.7	4.6
15	13.9	9.8
16	20.7	9.7
17	26.3	10.8
18	24.3	10.9
19	20.9	12.2
20	20.0	4.9
21	2.4	4.4
22	21.5	8.3
23	22.7	8.5
24	32.0	1.7
25	28.2	8.3
26	23.1	8.1
27	24.9	7.1
28	23.5	7.3
29	23.4	7.0
30	31.6	4.7
31	16.0	1.8

APPENDIX B.

Average wind direction and speed at Wurtsmith AFB,
latitude 44° 26' N, longitude 83° 22' W.
(Wind speed is given in knots)

Month: January

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	27.8	7.2	16	28.4	7.3
2	22.7	5.5	17	6.8	13.9
3	23.3	4.6	18	20.6	5.4
4	24.1	6.9	19	22.0	3.9
5	22.8	7.8	20	10.1	6.7
6	23.6	5.3	21	23.7	9.0
7	25.4	10.0	22	7.0	3.1
8	22.8	3.8	23	26.0	4.4
9	32.3	6.1	24	24.1	7.6
10	34.1	4.9	25	22.7	5.4
11	34.6	8.4	26	13.3	4.2
12	28.1	8.1	27	24.0	5.6
13	20.6	9.3	28	25.3	3.6
14	22.1	12.0	29	21.1	7.4
15	13.7	6.7	30	21.0	10.7
			31	26.2	14.5

Month: February

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	32.7	4.2	16	23.8	6.7
2	2.4	11.7	17	31.8	6.0
3	8.6	9.6	18	18.9	6.0
4	0.4	8.6	19	31.1	6.1
5	35.1	6.4	20	24.7	4.8
6	3.0	12.8	21	13.3	5.9
7	36.0	6.3	22	2.8	14.7
8	10.5	1.2	23	30.2	9.3
9	33.5	4.2	24	34.5	6.1
10	23.7	9.7	25	31.3	4.1
11	24.7	8.1	26	21.0	3.7
12	20.8	3.1	27	19.2	7.5
13	32.1	8.4	28	22.7	7.6
14	2.9	6.5			
15	19.6	3.2			

(continued).

APPENDIX B. (continued).

Month: March

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	4.1	6.7	16	2.0	16.1
2	9.3	1.5	17	32.0	13.7
3	16.7	8.4	18	23.8	8.8
4	21.1	3.9	19	31.7	9.0
5	22.6	7.0	20	3.7	5.6
6	19.7	10.8	21	27.8	7.4
7	31.9	6.6	22	20.9	6.6
8	9.6	13.1	23	26.3	10.3
9	21.7	4.7	24	27.0	8.5
10	35.0	9.5	25	20.7	12.3
11	16.8	4.8	26	27.9	9.9
12	4.0	13.1	27	28.8	4.5
13	0.3	8.5	28	6.2	9.0
14	25.8	5.3	29	9.7	10.2
15	12.9	4.3	30	4.8	10.6
			31	31.5	8.3

Month: April

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	6.3	11.1	16	30.3	7.8
2	31.5	9.6	17	24.8	10.8
3	5.9	7.6	18	1.0	8.7
4	21.8	11.2	19	8.3	3.0
5	32.3	10.1	20	17.5	6.7
6	25.4	7.1	21	19.7	11.7
7	33.3	5.9	22	20.7	10.3
8	3.7	11.9	23	32.3	9.1
9	2.0	8.5	24	35.8	6.0
10	23.2	4.0	25	22.3	6.7
11	8.9	5.5	26	6.3	2.5
12	14.9	6.6	27	19.3	6.8
13	21.5	7.6	28	22.1	8.9
14	1.8	9.5	29	14.1	3.6
15	31.5	10.4	30	9.8	4.1

(continued).

APPENDIX B. (continued).

Month: May

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	33.4	8.7	16	11.0	6.0
2	15.5	4.9	17	1.7	4.1
3	28.7	8.1	18	1.6	7.4
4	10.6	4.5	19	4.0	8.7
5	2.8	3.5	20	10.8	5.2
6	33.9	9.2	21	19.5	5.7
7	35.0	7.2	22	25.3	7.9
8	11.0	6.1	23	24.8	12.5
9	7.4	14.0	24	27.8	11.4
10	12.5	4.8	25	23.8	7.8
11	17.9	6.8	26	3.2	6.7
12	24.8	12.1	27	17.5	5.0
13	25.4	11.9	28	23.0	7.0
14	19.9	9.1	29	2.9	6.6
15	22.4	10.4	30	5.6	7.3
			31	25.3	9.3

Month: June

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	11.0	3.7	16	22.9	5.9
2	11.5	4.9	17	21.6	8.6
3	14.5	3.6	18	20.1	6.8
4	21.2	9.5	19	17.8	6.4
5	20.9	7.1	20	24.0	7.3
6	15.5	6.3	21	4.8	6.0
7	16.3	8.4	22	0.7	9.8
8	15.2	8.9	23	2.0	9.6
9	11.3	7.7	24	1.6	8.0
10	20.6	11.3	25	1.5	8.3
11	29.3	11.5	26	3.2	6.2
12	24.3	8.8	27	13.0	2.7
13	26.3	6.1	28	10.0	3.3
14	20.1	6.3	29	20.3	3.9
15	20.0	4.6	30	25.5	9.1

(continued).

APPENDIX B. (continued).

Month: July

Date	Avg. Wind Direction	Avg. Wind Speed
1	23.5	7.2
2	20.1	9.8
3	25.5	11.3
4	25.5	8.2
5	24.2	7.6
6	22.0	5.7
7	20.2	5.2
8	23.2	5.5
9	16.5	7.6
10	4.6	7.2
11	14.0	5.2
12	20.8	4.5
13	21.3	6.3
14	16.4	7.1
15	0.2	9.3
16	9.2	4.2
17	19.6	5.5
18	25.9	9.0
19	35.7	7.8
20	3.0	6.2
21	10.0	2.7
22	7.2	1.5
23	19.8	4.3
24	3.3	3.8
25	16.2	3.4
26	20.0	6.9
27	25.0	5.0
28	23.7	8.7
29	31.8	6.9
30	26.3	6.5
31	28.0	6.8

Month: August

Date	Avg. Wind Direction	Avg. Wind Speed
1	15.2	3.9
2	18.4	4.1
3	20.3	6.3
4	23.7	5.7
5	23.3	6.7
6	20.6	4.3
7	22.2	3.7
8	22.3	1.1
9	2.0	5.6
10	8.3	5.0
11	16.0	8.0
12	22.3	6.4
13	2.8	4.7
14	1.8	7.2
15	11.7	2.8
16	23.7	3.9
17	27.0	4.6
18	27.0	5.0
19	12.0	3.0
20	19.0	2.8
21	20.3	4.6
22	20.0	6.7
23	34.3	4.5
24	00.0	4.0
25	16.3	3.8
26	23.4	6.2
27	28.2	2.3
28	2.6	3.3
29	28.5	3.2
30	17.8	4.0
31	24.2	8.2

(continued).

APPENDIX B. (continued).

Month: September

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	32.8	5.0	16	24.0	5.7
2	26.7	2.5	17	28.9	5.3
3	34.2	5.3	18	8.0	5.5
4	26.0	3.5	19	29.9	7.3
5	11.5	2.0	20	34.9	5.3
6	8.3	2.1	21	28.1	7.6
7	11.5	1.1	22	31.3	7.0
8	21.4	5.0	23	20.5	3.2
9	34.3	4.4	24	20.8	12.3
10	16.3	5.4	25	26.3	8.9
11	20.9	10.3	26	18.8	6.9
12	0.7	3.6	27	19.7	6.4
13	27.9	7.9	28	20.0	3.2
14	23.3	7.0	29	29.6	9.8
15	26.6	11.6	30	29.5	2.4

Month: October

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	32.8	6.9	16	21.6	5.9
2	33.0	4.6	17	29.3	12.3
3	25.0	4.3	18	0.7	5.8
4	12.0	7.2	19	32.2	2.0
5	21.0	10.7	20	34.0	3.7
6	18.5	7.4	21	21.8	6.7
7	29.6	8.9	22	27.0	9.0
8	18.1	4.0	23	29.3	1.3
9	29.3	3.3	24	21.0	6.0
10	18.9	4.2	25	28.8	8.7
11	20.7	4.8	26	23.7	6.0
12	32.9	7.4	27	4.5	2.7
13	15.3	1.4	28	21.7	4.4
14	23.1	9.0	29	17.5	4.4
15	27.2	5.5	30	19.7	5.9
			31	21.7	5.1

(continued).

APPENDIX B. (continued).

Month: November

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	11.3	6.0	16	22.0	8.0
2	7.4	3.2	17	22.9	10.1
3	28.7	1.8	18	21.0	3.8
4	33.0	1.3	19	18.1	3.8
5	1.9	5.9	20	26.2	6.4
6	27.5	3.3	21	33.1	11.6
7	23.1	4.3	22	23.7	5.3
8	19.3	2.2	23	20.7	7.7
9	20.0	3.2	24	35.1	6.3
10	16.1	2.4	25	33.7	7.2
11	17.2	7.3	26	25.1	6.3
12	25.8	4.1	27	16.8	8.3
13	23.4	8.8	28	27.3	5.7
14	23.2	9.1	29	33.4	4.0
15	23.1	13.2	30	7.0	6.4

Month: December

Date	Avg. Wind Direction	Avg. Wind Speed	Date	Avg. Wind Direction	Avg. Wind Speed
1	6.1	11.0	16	18.6	7.7
2	1.8	9.0	17	24.6	7.1
3	33.4	8.2	18	24.1	9.0
4	26.3	4.3	19	32.4	3.2
5	21.8	3.4	20	22.7	3.0
6	20.0	5.9	21	23.7	1.5
7	14.8	2.4	22	20.1	6.9
8	32.3	8.9	23	21.0	8.9
9	30.1	8.0	24	24.8	2.5
10	22.5	6.1	25	27.6	8.4
11	20.9	5.3	26	23.1	11.7
12	24.3	1.8	27	23.7	9.5
13	2.8	3.9	28	22.2	8.0
14	4.6	4.3	29	22.9	7.0
15	12.3	6.9	30	25.9	5.3
			31	20.9	2.9